Renewable-based isolated microgrids instead of replacing existing MV lines supplying rural areas

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Abstract

Spanish medium voltage (MV) lines supplying rural areas are approaching the end of their lifetime. A replacement of these assets will soon be needed. However, those areas' low population densities make the distribution system very long, leading to a very high investment per customer supplied. This master thesis explores the possibility of using renewable-based isolated microgrids, with photovoltaics (PV) and Li-ion batteries, as a replacement of MV lines in those areas. A techno-economic study is performed to find the threshold distance and load from which the microgrid is a better option. As a first step, the behavior during an entire year of different communities is simulated using a load forecast model. This model's output is used together with techno-economic parameters of solar PV and Li-ion technologies to optimize the microgrid's assets size, using *Prosumer* as the optimization software. Ultimately, the project's total costs of the microgrid are obtained. Later, the project cost of building the MV lines is compared to those of the microgrid to obtain the threshold distances and loads that define the optimal project to consider. It is concluded that the approximate distance of MV line that can be built per each customer is 187 meters. For projects where the length per customer is greater than that, it is economically preferable to build a microgrid. At the end of the thesis, sensitivity studies are performed on the business case's main uncertainties. Different options are considered to reduce the microgrid costs and make the business case more favorable.

Keywords: Microgrid, MV line, Load Forecast Model, Renewable system, Rural, Isolated

Resumo

As linhas de média tensão (MT) da rede espanhola que abastecem áreas rurais estão a chegar ao fim da sua vida útil. Em breve, será necessária uma substituição desses ativos. No entanto, as baixas densidades populacionais das áreas rurais tornam o sistema de distribuição muito extenso, levando a um investimento elevado por cliente fornecido. Esta dissertação de mestrado explora a possibilidade de utilização de microrredes isoladas de base renovável, com painéis fotovoltaicos (PV) e baterias de iões de lítio (Li-ion), em alternativa às linhas MT para abastecimento de áreas rurais. Um estudo técnico-económico é realizado para encontrar a distância limite e a carga a partir da qual a microrrede é a melhor opção. Em primeiro lugar, o comportamento de diferentes comunidades durante um ano é simulado usando um modelo de previsão de carga. A saída deste modelo é usada em conjunto com parâmetros técnico-económicos das tecnologias solar PV e Li-ion para otimizar o tamanho dos ativos da microrrede, usando o *Prosumer* como software de otimização. Posteriormente, o custo do projeto de construção das linhas MT é comparado com os da microrrede para obter as distâncias e cargas limite que definem o projeto ideal a ser considerado. Conclui-se que a distância aproximada de linha de MT que pode ser construída por cada cliente é de 187 metros. Para projetos onde o comprimento por cliente é maior, é economicamente preferível construir uma microrrede. No final da tese, são realizados estudos de sensibilidade cobrindo as principais fontes de incertezas. Diferentes opções são consideradas para reduzir os custos e tornar o caso mais favorável.

Palavras-chave: Microrrede, linha MT, modelo de previsão de carga, sistema renovável, rural, isolado

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List of Abbreviations

AC Alternating Current

BU Business Unit

CAPEX Capital Expenditure

CREST Centre for Renewable Energy Systems Technology

DC Direct Current

DoD Depth of Discharge

DSO Distribution System Operator

ETaaS Engineering Tool as a Service

HOMER Hybrid Optimization of Multiple Energy Resources

IEA International Energy Agency

IRENA International Renewable Energy Agency

LV Low voltage

LCOE Levelized Cost of Energy

MV Medium Voltage

NPC Net Present Costs

NREL National Renewable Energy Laboratory

OECD Organization for Economic Co-operation and Development

OPEX Operational Expenditure

USD United States Dollar

TRNSYS Transient System Simulation Tool

VRF Vanadium Redox Flow

PV Solar Photovoltaic

PVGIS Photovoltaic Geographical Information System

RES Renewable Energy Source

ROI Return On Investment

T3A	Tractebel Advisory and Advanced Analytics
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital

1. Introduction

Electrical power is the foundation of modern industrial society. Electricity is a very versatile way to transfer energy, and it has been used in an uncountable number of applications. All began in the second half of the 19th century when the incandescent light bulb's invention led to one of the first publicly available electricity applications: lighting. Not long after, at the beginning of the 1880s, the first power plants were being built. In 1882, Thomas Edison opened the first electric power plant aiming to sell electricity to the people who bought his light bulbs in New York City, which could lit up 400 lightbulbs at first.

The rapid expansion at that time completely transformed industry and society, leading to the Second Industrial Revolution. Since then, the grid that carries electricity to our houses has been modernized and expanded to many people globally, making it essential to modern society due to its limitless set of applications, including lighting, heating, transport, communications, and many others.

Electricity has become a human right, essential for a dignified life, that has been recognized constitutionally in many countries and several international treaties since the second half of the 20th century. In September 2015, the United Nations' General Assembly included it in its agenda for Sustainable Development Goals 2030, being the target to ensure universal access to affordable, reliable, and modern energy services [1].

Moreover, it has been shown that electricity is crucial for developing a country's industry and economy up to the point that its demand can be used to indicate the country’s development condition [2].

In Spain, the cities and industries' electrification began at the end of the 19th century and continued during all the 20th century [3]. The residential electrification had very different paces in urban and rural areas due to the low rentability of the electric system in rural environments, where long lines are required to supply a few customers. In the second half of the 20th century, when all the cities already had access to electricity, there were still hundreds of unelectrified villages. Several National Development Plans were promoted to electrify all the population. In 1972, the 3rd National Development Plan [4] was approved. This document included a Rural Electrification Plan, detailing the financial needs and exposing some data on the country's rural electrification progress. According to the document [5], in the year 1972, 230 thousand Spanish people still did not have electricity. Moreover, only eight provinces (out of fifty) had electricity in all the dwellings. The most extreme case was Andalucía, in the south of Spain, where 3.6% of the rural population did not have access to electricity.

Although many efforts were made, it was not until the beginning of the 1980s when the vast majority of rural areas were electrified [6].

When this thesis is being written (2020), the last distribution assets built to reach the most isolated places in Spain, under the Rural Electrification Plan (1972), have been in use for 40-50 years. Taking into account that the useful regulatory life of distribution assets (lines, transformers, substations, etc.) is 40 years [7], it is safe to assume that most of that assets are already arriving at the end of their useful life and need replacement in order to keep the safety standards required for critical assets like these. However, as happened in the past, the high price per customer of the rural distribution system may delay the grid's replacement, leading to dangerous conditions for the people and the environment.

In addition to this problem, the migration of the population from a rural environment to cities worsens the outlook. Since the 1950s, a massive migration process happened in Spain due to the industrialization process that the country was experiencing. During these decades, the rural population decrease has been dramatic, around 40% on average, with the most affected areas exceeding a 50% population loss [8]. The problem becomes even more severe when the migration is done by young people, resulting in the aging of the rural population. According to the projections made by the National Statistics Institute [9], this trend is not expected to change in the following years. Furthermore, several villages are at risk of being deserted in the next decades.

Consequently, Spain is by far the country in the South of Europe with a broader area sparsely populated. More than 50% of its territory has a density below 12.5 people per km^2 [8]. In other words, 53% of the Spanish territory is occupied by only 5% of the population. There are regions with a population density that can only be compared with the Finnish Lapland region, reaching a density as low as 4 people per km^2.

Summarizing, the extremely low densities lead to very long MV lines, making the cost per customer very expensive. Adding the risk of total abandonment of the village in the near future makes the business case very risky and not profitable from an economic point of view. However, due to the old system, the investment must be made to preserve the system's safety and security requirements, leading to a considerable money expense.

This master’s thesis studies the possibility of solving this problem using microgrids.

According to the United States Department of Energy definition, a microgrid is a group of interconnected loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads) within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid [9]. A microgrid can connect and disconnect from the grid to operate in both grid-connected and island mode. Microgrids are playing an essential role in the transition from the traditional centralized generation to a more flexible and efficient distributed generation system.

When connected to the main grid, microgrids improve the security of supply and provide ancillary services [10]. Therefore, they are often used in places where having a continuous and reliable electricity supply is important, such as hospitals, scientific labs (universities), jails, or military bases.

The second thing that makes microgrids an interesting concept is the ability to supply power to remote areas, like islands far from the coastline, settlements in the middle of a desert, or villages surrounded by mountains, where grid isolated microgrids can be implemented.

According to IRENA [11], the number of people served by off-grid renewable energy solutions globally in 2016 was approximately 133 million people, a significant increase compared with the 20 million in 2011. Among those, there are systems from 10 kW up to 10 MW, including solar, hydro, wind, biomass, and hybrid microgrids, which are a combination of renewable generators and diesel engines.

According to the same document, off-grid technologies are mainly used to expand electricity access throughout the world. The dramatic cost reduction, technological advancement, and enabling policies have made it a great option to electrify those parts of the world where access to electricity is still a privilege. This is why most of these off-grid solutions are usually built in poor and developing countries, like South America, the south of Asia, and Africa. As reported by the International Energy Agency (IEA 2017) [12], 40% of the new electricity connections will be performed through mini and microgrids in the period between 2016 and 2030.

In this thesis, the possibility of implementing an isolated microgrid instead of replacing the medium voltage (MV) line in remote rural areas in Spain is explored. Some of the beneficial effects that this change would have are:

- Reduction of the costs per customer of the distribution system in rural areas. Furthermore, if the village happens to be deserted after some years, assets can be reused.
- Reduction of the electricity transportation losses, since they dispose of the usual long path from the generating sources to the loads. At the same time, this helps in increasing the overall energy efficiency of the system.
- In the case of renewable microgrids, they can also help in increasing the penetration of renewable energy sources in the system, making a more environmentally friendly system. This is in line with the Paris agreement [13], where Spain committed to reducing its greenhouse emissions by 40% in 2030 (compared to 1990).

The type of microgrid that is going to be simulated and compared with the MV line option will be completely renewable-based. Taking advantage of Spain's great solar potential, the only generating asset considered will be solar photovoltaic modules (PV). For energy storage, a Lithium-ion battery is going to be used.

Several renewable-based isolated microgrid studies have been done up to date. However, most of these studies aim at supplying isolated communities in developing countries, where electricity access was not available before. In this case, and taking advantage of the aged distribution system, the feasibility of building an isolated microgrid in a developed country instead of the replacement of the MV lines will be done, which is an innovative concept not widely explored until now.

Therefore, the main question that wants to be answered in this master thesis is:

- Is it economically feasible to supply the customers in these villages with a microgrid instead of a renovation of the distribution network? What are the necessary conditions (distance to the grid and size of the community) to have a positive business case?

To answer these questions, the following objectives have been set:

- Development of a customizable load forecast model for rural households;
- Optimization of asset size with *Prosumer* and estimation of total microgrid costs as a function of the community size;
- Estimation of the costs of building an MV line;
- Identification of threshold distance and load that make microgrid business case favorable versus the construction of MV lines;
- Assess the robustness of the business case by performing sensitivity analyses.

The innovative contributions of this thesis, compared with previous studies, are:

- The adaptation and use of a highly-customizable pseudo-random load forecast model to simulate the load of small communities. This innovation allowed to have a very realistic input for the optimization of the assets. This input was unavailable on the internet. The same model can be used in the future for the estimation of load profiles of small communities.
- The study of a renewable-based isolated microgrid in a developed country. A lot of research has been done on microgrids. However, the most common studies for isolated microgrids are focused on developing countries, aiming to increase the electrification rate. On the other hand, in developed countries, the studies are related to distributed generation's benefits on the main grid, thus focusing on grid-connected microgrids. Therefore, isolated microgrids are not under the focus in developed countries, and several interesting applications can still be found.

- The concept of substituting MV lines with microgrids is also innovative. Identifying the potential of the solution in developed countries may be a change that can help in many ways: environmentally, economically, and socially. This business case can be replicated in many other developed countries, using the available renewable resources in each location.

The structure of this thesis is as follows. In Chapter 2, the literature review can be found, where similar studies are analyzed and summarized. In Chapter 3, the methodology followed to run the simulations is explained. A shallow explanation of the software used and the sources of all the inputs used in the simulation are given. Furthermore, an in-depth explanation of the load forecast model and all the changes and adaptations made can be found. In Chapter 4, the results of the simulations are presented and discussed. Afterward, the total discounted costs of the microgrid and MV business cases are computed. The comparison of both cases and the identification of the threshold distances are also given. Several sensitivity analyses can also be found, covering the main uncertainties of the business case. At the end of the chapter, other controversial microgrid-related topics are discussed. In Chapter 5, the conclusions of the study can be read.

2. Literature Review

In this section, a literature review on the techno-economic analysis of microgrids will be performed. The methodology and inputs of the most recent research papers on the topic will be analyzed, and the differences with the proposed microgrid in this thesis will be highlighted.

Two different categories can be distinguished for the optimization software used for the simulation, the public, and the private ones, the latter developed within companies for exclusive use. There are many types of public software programs that simulate and optimize energy systems including renewables, like *HOMER* [14], *Hybrid2* [15], and *TRNSYS* [16]. Among them, the most popular by far is *HOMER* (Hybrid Optimization of Multiple Energy Resources), the software developed by NREL (National Renewable Energy Lab).

Nonetheless, in the case of this thesis, *Prosumer* has been used. It is an internal software developed within *Engie Impact* and has been used to optimize the assets' size (more information in Methodology chapter).

After examining and classifying the most relevant scientific articles published related to microgrids, it has been observed how most of the articles have common characteristics. The vast majority are using *HOMER* as the optimization software for their microgrids. It can also be seen how most of the studies related to stand-alone microgrids take place in developing countries located in Asia, South-America, or Africa. Another trend is that the case studies use to be about relatively big communities, with more than 100 people living in them. The most considered generating technology is by far PV because it is a resource with big potential in many developing countries, followed by wind energy, diesel (in combination with renewables), biomass, and biogas.

Therefore, this literature review will be focused mainly on the studies made in developing countries. This fact has significant importance for two details. Firstly, in developing countries, load growth is always expected, and the microgrid has to be sized and designed accordingly. Meanwhile, in developed countries' rural areas is usually the opposite, and load is expected to decrease during the project lifetime due to the migration to cities. Secondly, the economics are very different. The certainty and accuracy of the asset prices are much higher in developed countries. As a result, the Weighted Average Cost of Capital (WACC), which is the project's expected return rate, is considerably smaller because the risk on the project also decreases.

Moreover, the fact that very small communities are generally not considered makes the difference. For example, the load profile on large communities during the year can be easily estimated because of the averaging effect of big groups of people. It also makes the difference in the feasible technologies to be considered because the energy to be supplied is much higher. This makes it possible to design a more diverse system, where more than one or two technologies can be included simultaneously.

In [17], Masrur et al. studied the optimal configuration of a mini-grid in an island in Bangladesh with 8000 inhabitants being deficiently powered by diesel generators. The authors performed a techno-economic analysis to minimize the net present cost of the project. A bottom-up approach was used to estimate the consumers' load profile, taking into account the community's most owned appliances. Results show that a system combining PV, wind turbines, diesel generators, and battery (hybrid mini-grid) seems to be the most feasible solution in terms of costs (30% cheaper than the diesel-only solution) and environmental respect (23% CO_2 emissions reduction).

Veilleux et al. [18] made a study aiming to redesign and refinance a microgrid in an island with 400 inhabitants in Thailand, based on PV, batteries, and diesel generators. Different scenarios were created by them, with different battery technologies and system configurations. To simulate the load, real measurements on the island demand were used. The study results revealed that Li-ion batteries are the best technology to increase the system's renewable fraction. However, this implied a higher overall price of the system in comparison with the diesel-only system. The optimum scenario was a DC-coupled system using Li-ion batteries, achieving a Levelized Cost of Energy of 0.220 €/kWh.

Haghighat et al. [19] performed a techno-economic analysis for microgrids in 3 remote villages in Colombia, having 800, 430, and 520 inhabitants. Three different scenarios were created for the sake of comparison: diesel-only, RES-only (PV, wind, and battery), and hybrid system. They used a synthetic hourly load to perform the optimization. They concluded that a hybrid system with PV, battery, and a diesel generator would be optimal. With that kind of system, the renewable fraction was 99%, and the system's carbon footprint was just 2.6% of the diesel-only system. However, the cheapest option was the diesel-based system, with nearly half of the hybrid option price. For the RES-only system, the main barrier was high capital costs.

Vendoti et al. [20] made a techno-economic analysis for off-grid solar, wind, biogas, biomass, fuel cell, and battery systems for electrification of 400 households in Karnataka, India. They wanted to minimize the system's net present cost and provide reliable, continuous, and sustainable electricity. The load was estimated to be around 724 kWh/day from surveys to the inhabitants, considering as well the future growth. The final result revealed that the best option was to build a system with all the considered technologies simultaneously, which Cost of Energy would be 0.214 $/kWh.

Kaur et al. [21] compared an isolated and grid-connected microgrid composed of PV, biomass generator, and battery for a community with 236 households in Punjab, India. The idea was to profit from the huge potential biomass generation has in India's rural parts. The load profile was estimated for summer and winter from surveys to the inhabitants of the community. The main conclusion of the study was that biomass and PV generation is an effective combination. More specifically, the grid-connected microgrid achieved a Cost of Energy of 0.0735 $/kWh, 1.37 times cheaper than the main grid. Moreover, the emissions were reduced by almost 80%. For the isolated system, the Cost of Energy was 0.1568 $/kWh, considerably higher than the grid-connected one.

Analyzing all the previous articles as a whole, it can be extracted that for isolated systems for big communities in developing countries, usually the best result economically and environmentally is given by a combination of renewables and diesel generator. A microgrid with only RES would have to overcome the weather uncertainties by oversizing the generating assets and storage capacity considerably. In most cases, it is economically advantageous to use small internal combustion engines to supply power in those hours of the year where the weather conditions, like the sun irradiation or the wind speed, are too low.

Some research articles were found focused on really small communities, summarized in the lines below.

In Ref. [22], Astriani et al. performed a techno-economic analysis of a small-scale microgrid (10kW) for an office building in Indonesia, considering only PV and battery. The main difference between this case and the current study is that this microgrid is considered connected to the main grid, therefore the reliability concerns are much lower, and the energy produced can be viewed as an income to the business case. Moreover, the considered load profile is not residential. The analysis outcome was that the business case to build such a microgrid would be only positive if incentives for RES were considered. Other aspects that could improve the case were to consider reliability income or carbon taxes.

Akinyele and Rayudu [23] made a techno-economic and environmental analysis of a PV microgrid for remote communities in Nigeria, conformed by 20 houses approximately. As the community is very small, the load profile was estimated through a survey to the community's inhabitants, asking for their appliances and behavior both in rainy and dry seasons, thus creating a standard demand profile for each of them. The system was modeled to support a yearly growth of 2%. The study concluded that with a system between 55 and 82.5 kW, the availability values achievable were as high as 97%, with a life cycle costs below 500 k$, approximately half of the diesel-only system's price and around 10% of its total emissions. The payback period was estimated to be 17 years.

Murty and Kumar [24] made a techno-economic analysis for a stand-alone system in Tamilnadu, India. The goal was to electrify around 30 households with the optimal system considering PV, Wind, battery, and diesel generators. The most economical system was found to be PV and battery. The Cost of Energy of the hypothetical system was higher than the one from the main grid, but with remarkably less emissions (68% reduction) than the diesel-only system.

Analyzing the studies related to very small communities, it can be concluded that they tend to be simpler than the bigger ones, having as an optimal solution in most cases a combination of PV and battery.

Some studies have been found in developed countries. However, to find analysis made on stand-alone systems was challenging. Moreover, all the studies found were made for relatively big communities, far from this thesis's scope.

In Ref. [25] (2016), Thomas et al. conducted a feasibility study for the electrification of a Greek island with 300 inhabitants. Three different scenarios were considered, with a variable penetration of renewable energies. One of the critical inputs, the load, was obtained directly from the DSO of the island. However, as the location is a tourist place, the system had to be prepared to supply many more customers in the summer season. The case with lower Net Present Costs (NPC) was the one with wind turbines, electrochemical batteries, and 400 kW diesel generators (1.8 million €). However, the carbon footprint was the highest. The second cheapest scenario was including PV to the previous case, which supposed an increase in the price (2.25 million €), but a significantly lower footprint (diesel gen-sets were nearly halved). For the last case, diesel generators were removed entirely; thus, the system had PV, wind generators, and batteries. That scenario was found to be technically feasible but required an enormous capacity of PV, wind, and storage, increasing the NPC approximately three times, up to 6.5 million €.

Hafez and Bhattacharya [26] also made a similar comparison between four different scenarios for a community in Waterloo, Canada. Its consumption was approximately 5000 kWh per day with an 1183 kW peak demand. The four different scenarios were diesel-only, RES-only, hybrid, and connected to the grid. The study results revealed that the hybrid system had the lowest net present costs of the first three options, followed by the RES-only and the diesel-only was the most expensive. However, the most economically favorable system was the one connected to the grid. They estimated that the threshold distance for the microgrid to be a favorable business case versus the grid extension was 150 km. This is because relatively big communities were treated.

In Scotland, the Isle of Eigg is still not connected to the power distribution grid located on the mainland [27]. The approximately 100 inhabitants have been operating their own stand-alone grid since 2008. They successfully converted their power supply, stepped away from diesel, and now generate power using virtually 100% renewable energy sources. The hybrid off-grid system equipped with an installed renewable power generation capacity of 166 kW integrates solar PV, wind power, hydropower, and a storage battery. If this is not sufficient, two diesel generators are used as a backup. Energy costs on the island have dropped more than 60 percent.

In developed countries, the only case where stand-alone microgrids are considered as an alternative is in the islands. There are not significant studies regarding the implementation of stand-alone microgrids to supply small communities in the rural areas of developed countries. To the best of the authors' knowledge, isolated microgrids have not been considered to date an option to substitute aging MV lines in isolated places.

Given all the research papers analyzed, the current thesis differentiates itself in the fact that the study takes place in a developed country, focusing on very small communities, below 100 inhabitants, and considers only stand-alone cases.

3. Methodology

In this chapter, the methodology followed to achieve the thesis's main goal will be explained. Then, an introductory explanation of *Prosumer* and its applications' scope will be done. Afterward, the inputs required to run the simulations, and all the sources of the values used will be given. At the end of the chapter, a detailed explanation of the load forecast model used to obtain the demand curve during all the year will be given, together with the other two options considered. The three options will be compared and the advantages and disadvantages exposed. Also, the details of the modifications done to the selected model will be explained.

3.1 Overview

In this section, an overview of the steps followed to achieve the thesis's goals is given.

First of all, the total costs for each of the options had to be computed to make the comparison between the MV line and the microgrid case.

On the first hand, the MV line costs depend mainly on the community's distance to the main grid. These costs were extracted from a publicly available document of the Spanish Government. A simplified formula for the costs per km was straightforward to obtain.

On the other hand, the microgrid cost is independent of the distance to the main grid. It will be affected mainly by the amount of electricity consumed in the community (i.e., inhabitants). The more electricity is consumed, the bigger the PV and battery capacities will be, leading to higher costs. Therefore, an optimization of the assets as a function of the community's size had to be performed. Ten different communities were simulated in the study, ranging from 3 to 30 inhabitants.

The assets' size (PV and battery) were optimized using an advanced simulation and optimization tool called *Prosumer*. With this software, the capacity and discounted costs of these assets were obtained.

The critical and most challenging input to get for the simulations was the community's load profile during the year, which had to represent the demand needs of a very small rural community in Spain. As extremely small communities are being considered, the averaged profiles available on the internet were useless. Moreover, they had to be tailored to rural communities. Therefore, a load forecast model was taken from the internet, and the code was developed and modified in order to satisfy the needs of the case. As a result, a very customizable and realistic way of representing individual household demand profiles was obtained.

Once the simulations were done, the rest of the microgrid costs were estimated (cables, electric equipment, design and commissioning of the microgrid, etc.). In the end, the microgrid project's total cost as a function of the yearly demand load was finally obtained.

As the last step, the two projects' costs were compared as a function of the distance to the grid and the community's size. From this result, the necessary conditions for microgrid implementation were achieved.

Besides, sensitivity analyses were done on the results to check the solutions' robustness under the case's main uncertainties.

3.2 Optimization software: *Prosumer*

Prosumer is an advanced simulation and optimization tool developed by Tractebel Advisory & Advanced Analytics (T3A) [28]. ENGIE Research has funded its development under the Energy System Simulation Thematic Lab frame hosted by Tractebel. The first Python prototype was created in 2012. It was then used for and enriched by various studies supporting ENGIE Business Units business. This advanced prototype was then turned into an Engineering Tool as a Service (ETaaS) approach in 2018 for direct involvement of the Business Unit users.

The tool aims at defining strategic planning for multifluid (i.e., heating, cooling, electricity, gas, mobility, water, waste, etc.) energy investments at the territory level. It designs the optimal configuration minimizing the total cost of ownership of the system. The tool's focus is on a strategic assessment of distributed energy projects (focus on pre-feasibility studies).

The tool plans, at different territory levels: industrial parks, campuses, eco-districts, regions, the optimal sizing and dispatching of all physical assets and provides key indicators of the resulting techno-economic performance: Return On Investment (ROI), Net Present Value (NPV), Levelized Cost of Energy (LCOE), Renewable Energy Source (RES) share (% of load), Environmental footprint/Avoided CO_2 emissions, etc.

Prosumer determines the optimal size of the different assets in order to fill the energy needs. One of the strengths of *Prosumer* is that the tool may consider any kind of energy fluids thanks to its genericity: common energy fluids (Hydrogen, electricity, heat, gas) but also more specific ones (chemicals, Ammonia, Oxygen, water, etc.) or very specific elements like mobility.

This genericity makes the tool very flexible. Therefore, it may be adapted to multiple business-to-business applications (industries, mines, airports, utilities, etc.) and public projects (Campus, villages, eco-districts, islands, etc.).

The tool integrates detailed physical modeling of the different equipment, including the technical constraints and the associated costs (both investment and operation). These additional constraints are integrated into a mathematical model (forming a mixed-integer linear program) that is solved using a state-of-the-art commercial solver.

The program minimizes the total cost of ownership (including all investment and operation costs) of the system while respecting all the assets' technical constraints and providing the defined loads of the different fluids. The problems are usually very large (depending on the number of equipment input by the user).

The tool provides different indicators to evaluate the optimal solution's quality, including the size of each equipment and how they should be operated to minimize the operation cost.

Different scenarios may then be studied using the tool to integrate specific constraints like a minimum RES share for the production. It allows the user to compare other possible solutions and make the best possible investment decisions.

Prosumer will optimize the assets to cover the hourly demand during all the year at all times, given an input load profile. Its ultimate goal is to arrive at a concise and clear investment decision.

As explained before, for this master thesis, the software has been used to optimize the asset size and estimate the microgrid's main assets' discounted price during the 40 years of the business case.

The main *Prosumer* inputs, explained in the section below, are:

- WACC and energy vector/s present in the microgrid (electricity, hydrogen, heat, etc.);
- Project duration and years to optimize;
- Hourly demand during the entire year;
- Equipment:
    - generators: economic and technical parameters;
    - storage: economic and technical parameters;
- Commodities: the price of fuel, CO_2 emissions, or grid connection;
- Reserve requirement (optional);
- Regulation assets (optional).

Limitations

Since *Prosumer* is an in-house built software developed and funded by Engie, the specific information about the model and its detailed structure is confidential and was not disclosed.

3.3 Simulation conditions

For this master thesis, the inputs will be adapted to the rural, isolated microgrid case located in Spain. The simplest business case's feasibility has to be checked as a first approach to the problem; therefore, the only generating asset considered will be PV, combined with Lithium-ion battery storage to supply the load whenever PV power is not available. If a positive result is obtained, other generation methods and storage technologies are going to be considered to see the costs’ evolution.

In the following paragraphs, the inputs used for the simulation as well as their sources will be given and explained.

3.3.1 Weighted Average Cost of Capital (WACC) and energy vector

The Weighted Average Cost of Capital represents the expected return rate that the investor expects to receive on the project. The external market dictates this value.

According to the document, *Renewable power generation costs in 2018* [29], made by IRENA, the expected WACC for OECD countries and China on renewable generation projects is 7.5%. Therefore, as the base case study will be located in Spain, WACC will be considered 7.5% for all the simulations.

Regarding the energy vector, as a first approach and for the sake of simplicity, only electricity will be considered. In the future, hydrogen, heat, or even diesel could be added to improve the business case.

3.3.2 Project duration and years to optimize

The project duration will be set to 40 years, on the grounds that it is the average lifetime of some of the critical assets that are being considered, such as the MV line [30].

Prosumer has an option that allows optimizing the microgrid configuration more than once during the project's lifetime. This feature makes it possible to consider the evolution of the assets' prices and technical characteristics due to technological advancements. However, in this case, the optimization will only be done once at the beginning of the project, which means that the asset configuration (amount of PV and battery power and energy installed) will be constant during the 40 years of duration of the project. Consequently, the price of the assets forming the microgrid, like the PV panels and the batteries, will be considered constant. Therefore, when the assets have to be replaced at the end of their respective lifetimes, no learning curve is applied to the prices. They will be the same as at the beginning of the project but discounted.

3.3.3 Hour-resolution demand during the entire year

The hour-resolution demand during all the year is one of the key inputs of the simulation. *Prosumer* imposes the input demand to be always met, and an unrealistic power demand profile could easily lead to a misleading final result. At the same time, it is the most complex input to obtain of all due to the lack of data on the internet on small rural communities.

The goal is to have as an input the demand of small communities (from 1 to 10 houses) in a rural environment. The averaged load that is possible to obtain on the internet would not be adapted to such a case for two reasons. First of all, small communities' demand profiles have high-frequency variations created by the households' different appliances, which will differ substantially from the averaged demands for dwellings across the country available on the internet. Secondly, the data available does not consider the behavioral differences in rural locations; they represent the most common profile of a household in an urban environment. Moreover, the fact that the load for all the year is needed only adds more difficulties when looking for a suitable input online.

Considering all the obstacles arising, a different approach was taken. Making a simulation of the households during all the hours of the year was considered the best solution possible in terms of realism and customizability for future sensitivity studies.

As this kind of load forecast model is quite complex, the best way to proceed was to find a publicly available model and adapt and develop it to fulfill this case's specific needs. Finally, a highly customizable model made with Visual Basic (Excel) was found, developed by Richardson et al. [31] and belonging to the Center for Renewable Energy Systems Technology (CREST), in Loughborough University, United Kingdom. The model is openly available to download on the internet [32] under the following license [33].

The model was modified to the needs of the case in order to obtain as a final output the hourly load of ten hypothetical communities living in southern Spain during all the year, having from one to ten households.

An extended explanation of the model and the modifications done can be found in section 3.4 below.

3.3.4 Generating assets: Solar PV

As mentioned in the introduction, the feasibility of the most straightforward case should be obtained. Therefore, the only generating asset considered for the microgrid was solar PV. This decision was made due to the high potential of this technology in Spain, as well as its maturity and proven feasibility in numerous renewable projects. In addition, costs in the future are expected to keep decreasing [34].

For solar PV, two main inputs were needed for *Prosumer*:

- Firstly, the energy generation profile during all the year per kWp (kilowatt peak) installed, with an hourly resolution.
- Secondly, several technical and economic parameters of the modules.

On the first hand, the generation profile of the PV panels per kWp installed was needed. This profile was extracted from the Photovoltaic Geographical Information System (PVGIS) [35], a tool provided by the European Commission. This tool is able to estimate the solar radiation arriving at the earth's surface using geostationary meteorological satellite data. Unlike ground sensors, which have a real measure of the irradiance, satellite data has to be estimated considering different factors.

The advantages of using such images are that solar radiation data can be obtained from the whole area covered by the satellite, with a resolution of a few kilometers. Moreover, a long time series is available for that kind of data, approximately 30 years or more. For PVGIS, an image per hour is used to obtain the hourly irradiance values.

However, this method also has some disadvantages, and they are related to the complex calculations and estimations that have to be done to obtain accurate solar radiation data. For example, several factors affect it, like water vapor, aerosols, and ozone. Also, in some conditions, the accuracy of the estimation is decreased. For example, in snowy regions or places where dust storms are usual, satellite images can be challenging to interpret. For an overview of the calculation methods used by the tool, see the research conducted by Mueller et al. [36], [37], and Gracia Amillo et al. [38].

The data produced from the satellite images are also checked against real measurements to get an idea of the uncertainty and validate the dataset. Depending on the location, it has been proofed that the uncertainty can vary from less than 1% up to more than 10% when conditions are not favorable.

Once the solar irradiance data is obtained, the energy output of the system is computed. In addition to the previous estimations done, several effects can also influence the energy output of a solar system. In the next lines, the effects considered by PVGIS will be briefly explained, as well as those not considered in the estimations.

PVGIS makes corrections for:

- Shallow angle reflection: It considers that the surface reflects a portion of the light arriving to the PV module. This portion depends on the angle, being maximum when the light hits the module with a direction close to parallel to the surface. This effect causes a loss of 2-4% of the sunlight.

- Changes in the solar spectrum: This depends on the technology of the PV modules being considered. Each technology has a different spectral response to different wavelengths. Some of them, like crystalline silicon, are more sensitive to near-infrared, while others, like amorphous silicon, are more sensitive to visible light. Therefore, the solar spectrum changes along the day affect the energy output of the system. For example, during the sunrise and sunset, sunlight is closer to red, and when the day is cloudy, the light received is closer to blue. This effect can increase or decrease the energy output depending on the location.
- PV power dependence on irradiance and module temperature: The PV modules' efficiency is affected by the irradiance. For low irradiances, the efficiency usually decreases comparing to standard conditions measurements (1000 W/m^2) because the modules are not designed to extract the maximum energy in such conditions. Also, high module temperatures negatively affect the module's efficiency compared with standard conditions (25ºC). The wind can also play a role in cooling the module. These effects also are dependent on the technology being considered.
- System losses and degradation with age: Typically, PV modules lose about 0.5% of power per year of operation, according to Jordan and Kurtz [39]. That is important to consider in the energy output calculation. Moreover, the system losses are always present. For example, the inverter and cables of the system do not have 100% efficiency. Part of the electricity flowing through them is lost in different ways and must be taken into account to obtain realistic values. This value is customizable because it can change from system to system, and the recommended value by the tool is 14%.

On the other hand, PVGIS does not make corrections for the following effects:

- Snow: Modules can be covered by snow, reducing the energy output dramatically.
- Dust and dirt: As with the snow, dust can reduce the energy output until it is cleaned or it rains.
- Partial shadowing: The energy output is also reduced when a module is covered partially or entirely by an obstacle, like a building or a tree. This depends mainly on the installation site.

Figure 1 shows the production profile chosen as an input for the simulation, which corresponds to a location in the south of Spain, with a latitude and longitude of [37,866; -4,529]. The energy output profile contained hourly values for a 1 kWp installation between 2005 and 2016. To select the most representative year of that period, the total yearly irradiation of each year was calculated. The year with total irradiation closest to the average value of all the years was finally selected (2009).

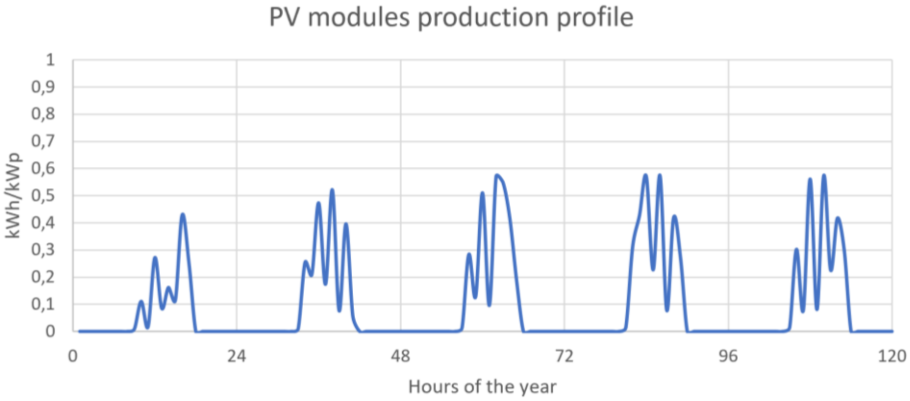


Figure 1 Extract of the PV production profile of the first 5 days of the year

The profile corresponds to a module with a fixed slope of 34°, and an azimuth of 3°, values calculated by PVGIS to obtain the maximum energy output. The chosen technology was crystalline silicon, and the system losses were set to the default recommended value, 14%.

On the other hand, some technical and economic parameters were needed for *Prosumer*. They can be seen in Table 1 and Table 2, respectively. The capacity loss refers to the percentage of capacity that is lost per year due to aging. The values were given by Laborelec [40] based on the state-of-the-art commercial PV modules. The economic parameters were extracted from the IRENA document, *Renewable power generation costs in 2018* [29]. The prices given refer to solar projects, including the modules themselves and the inverters, cables, or the installation, among others.

Table 1 Technical parameters of the PV panels

Technical Parameters	**Solar PV**
Capacity Loss [%/Year]	0.62

Table 2 Economic parameters of the PV panels

Economic Parameters	**Solar PV**
Build Cost Power [€/kW]	1000
O&M Cost Power [€/kW/y]	17
Technical Life [y]	25

3.3.5 Storage technology: Li-ion/VRF Battery

Regarding the storage technology of the microgrid, several different technologies were considered. The basic requirements that the storage technology had to fulfill for this case are:

- size below 500 kW, to supply small communities;
- cycle frequency between 0.5 and 1 per day, to use in combination with solar PV;
- low maintenance needs, to avoid frequent travels to isolated locations;
- long lifetime;
- not site-dependent so that a general solution can be obtained;
- ability to supply variable power, to match the load demand of the community at all times;
- low price, to make the system as cheap as possible.

Several different technologies were considered at the beginning, ranging from mechanical to chemical storage. Following the requirements listed above, mechanical storages like pumped hydro and compressed air were discarded because they are site-dependent. Discarding as well the high-temperature batteries, which are only efficient delivering constant power; nickel-based batteries, which have too high self-discharge; and lead-acid batteries, which need regular maintenance; the two final candidates remaining were Lithium-ion batteries and Redox flow batteries. Each of them had several advantages and disadvantages that will be summarized in the following paragraphs.

Figure 2 [41] shows the expected evolution of the costs and life cycles to 2030 (left) and the discharge time at rated power (right) of several storage technologies.

As can be seen in Figure 2, it is interesting to notice that both technologies are still in development and have a significant cost reduction potential, making the business case more favorable in the future.

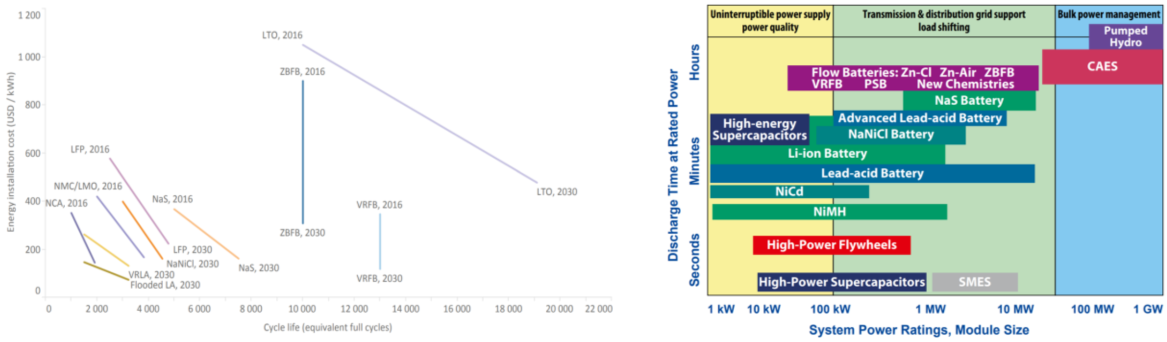


Figure 2 Energy installation costs and cycle life (left) and discharge time at rated power (right) for different storage technologies

On the first hand, Li-ion is a much more mature technology, which has been already used in several projects worldwide. This kind of battery has very high energy and power densities, making them perfect for applications with spatial constraints. One of the main advantages over Vanadium Redox Flow (VRF) batteries is their high round-trip efficiency, which is around 95%, much higher than the 70% achieved by the VRF [41]. Also, moving elements are not needed, which leads to less probability of failures and cheaper maintenance. Moreover, the fact that it is a much more mature technology makes the offer in the market much higher, with higher competition among manufacturers and more certainty on prices. As a consequence, the projects that include them are easier to finance.

On the other hand, Vanadium Redox Flow also stands out for several reasons. First of all, the batteries' energy and power can be scaled independently one from the other, making them perfect for applications with high discharge times, as shown in Figure 2 (right). The battery's energy can be adjusted to each case's needs by increasing or decreasing the size of the tanks where the electrolyte is stored, giving very long charge/discharge durations and no self-discharge. This leads to cheaper energy costs than in the Lithium-ion case, which is very useful in projects where a high amount of energy has to be stored, and there's no need for a very high supply of power. Another key advantage of this storage technology is its long lifetime, from 10000 cycles on. According to the most conservative estimations, this means that their life can be more than 20 years [41].

There also exists the possibility of rebalancing the electrolyte at the end of the storage lifetime, reducing the expense of substituting the battery. Figure 3 [42] shows the evolution as a function of time of the capacity retention of a VRF battery, using the rebalancing technique. In addition, unlike Li-ion batteries, there is no need for heat removal for VRF batteries because flow prevents thermal runaway. It is also safer because stopping its operation is as easy as stopping the flow, and vanadium is non-flammable, avoiding fires or explosions. The depth of discharge (DoD), unlike Li-ion batteries, is 100%, meaning that it can be discharged entirely without generating any problem. As a last advantage for this specific application, their significant size and weight may prevent them from being stolen, as they are kept outdoors.

Despite all the advantages and promising features of VRF batteries, the decision was taken to build the primary business case with Li-ion batteries due to its higher price certainty and maturity. However, sensitivity studies will be done with VRF to devise the benefits.

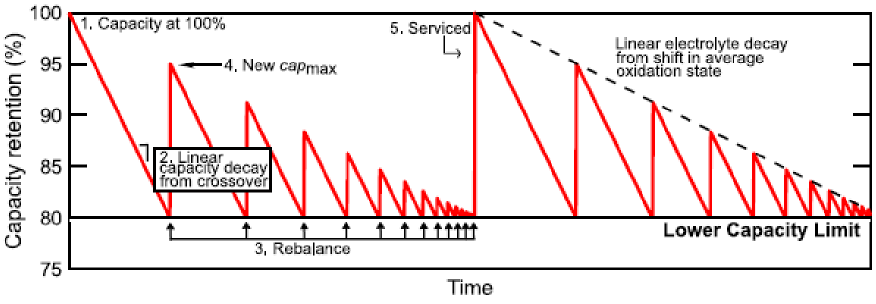


Figure 3 Example of VRF capacity retention as a function of time, using rebalancing technique

For the inputs needed in *Prosumer*, Laborelec values were again taken [40], based on the values for current projects currently under development. The inputs can be seen in Table 3 and Table 4.

The maximum Depth-of-Discharge (DoD) indicates the maximum percentage of the battery energy capacity that can be discharged. The energy-to-power ratio (E/P) is the time (h) that the battery can be in operation, supplying energy at the rated power.

Table 3 Technical parameters Li-ion battery.

Technical Parameters	**Li-Ion Battery**
Round-Trip Efficiency	85%
Max DoD	0.8
Capacity Loss [kWh/y]	0.02
E/P Range* [h]	0.25 - 10
Dissipation Rate [h^{-1}]	4e-5

**This range was increased from the original 0,25-4 to remove the constraints. Further discussion is provided in the results section.*

Table 4 Economic Parameters Li-ion battery

Economic Parameters	**Li-Ion Battery**
Build Cost Power [€/kW]	300
Build Cost Capacity [€/kWh]	300
O&M Cost Power [€/kW/y]	6
O&M Cost Capacity [€/kWh/y]	6
Technical Life [y]	10

3.4 Load forecast model

In this section, the three methodologies considered to obtain the hour-resolution demand during an entire year for the hypothetical communities, necessary in *Prosumer* as an input, will be explained and compared.

As seen in the literature review, researchers on similar topics have used different approaches. The most reliable one is to obtain the data directly from the DSO, not possible in this case due to confidentiality issues. Some others performed surveys to the communities to learn about their behavior and appliance configuration to simulate the demand, which would be time-consuming for this study. The last approach was to estimate the demand of big communities using the averaged consumption values of the appliances, not useful in small communities.

The need to develop a model for load forecasting arose when looking for suitable profiles on the internet. The load profile needed to accomplish mainly five requirements to be able to represent a real case:

- Climatic conditions similar to those in southern Europe, to obtain a realistic pattern of appliance use;
- Belonging to a rural community, because rural households have a lot of differences in behavior and appliance configuration comparing to their urban counterparts;
- Located in a developed country;
- Small-sized, because small communities load profiles have high-frequency variations and are unpredictable;
- Hour-resolution values during all the year, to use as an input in *Prosumer*.

Accomplishing all those fundamental requisites was not possible due to the lack of data. Therefore, the decision was taken to make a simulation of the demand.

Three approaches were evaluated to simulate the load, with different degrees of complexity and different inputs required. A comparison was made to decide the best method for this case.

3.4.1 Standard Profiles

The first approach is the simplest and more generalist one. This procedure is used in the Spanish electricity market to establish the load profiles that will be used to obtain the hourly measurements necessary for the settlement of energy in the electricity production market, based on the consumption data registered by non-hourly measuring equipment. DSOs apply them to those consumers that do not have meters with hourly record capacity [43].

Figure 4 shows the required inputs and the output of this method. Given as inputs the type of contracted tariff, the yearly demand of the household, and the real total demand of the electric system that year, the household's hourly demand profile during all the year can be obtained.

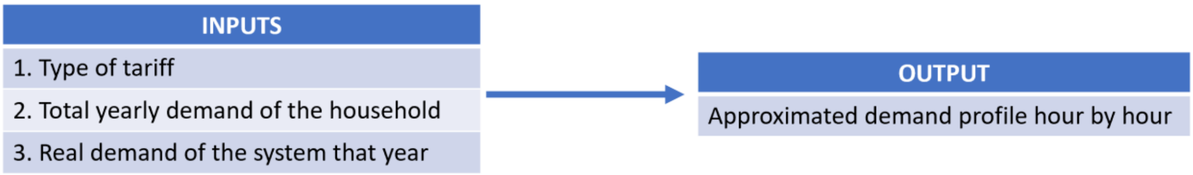


Figure 4 Required inputs and output of the Standard Profiles method

Type of tariff

The decree gives four different options depending on the type of tariff that the customer has contracted. The document classifies the customer into four groups:

- Type 1: Low voltage clients (less than 1 kV), with a contracted power lower than 15 kW and no discrimination periods.
- Type 2: Low voltage clients (less than 1 kV), with a contracted power lower than 15 kW and two discrimination periods.
- Type 3: Medium voltage clients (between 1-36 kV), with a contracted power lower than 450 kW and three discrimination periods.
- Type 4: Low voltage clients (less than 1 kV), with a contracted power lower than 15 kW and three discrimination periods.

Figure 5 shows the four initial profiles according to the type of tariff. Depending on the group, the initial profile will be different. The initial profile will be used as a base for the calculation of the final profile. Every year, they have different values that are published in an official document. The profiles are unitless, and after the corresponding modifications, it will have to be multiplied by the total yearly consumption of the household to obtain the demand profile.

According to recent data, in the south of Spain, 83% of the customers belong to type 1 customers [44]; that is to say, they do not have discrimination periods.

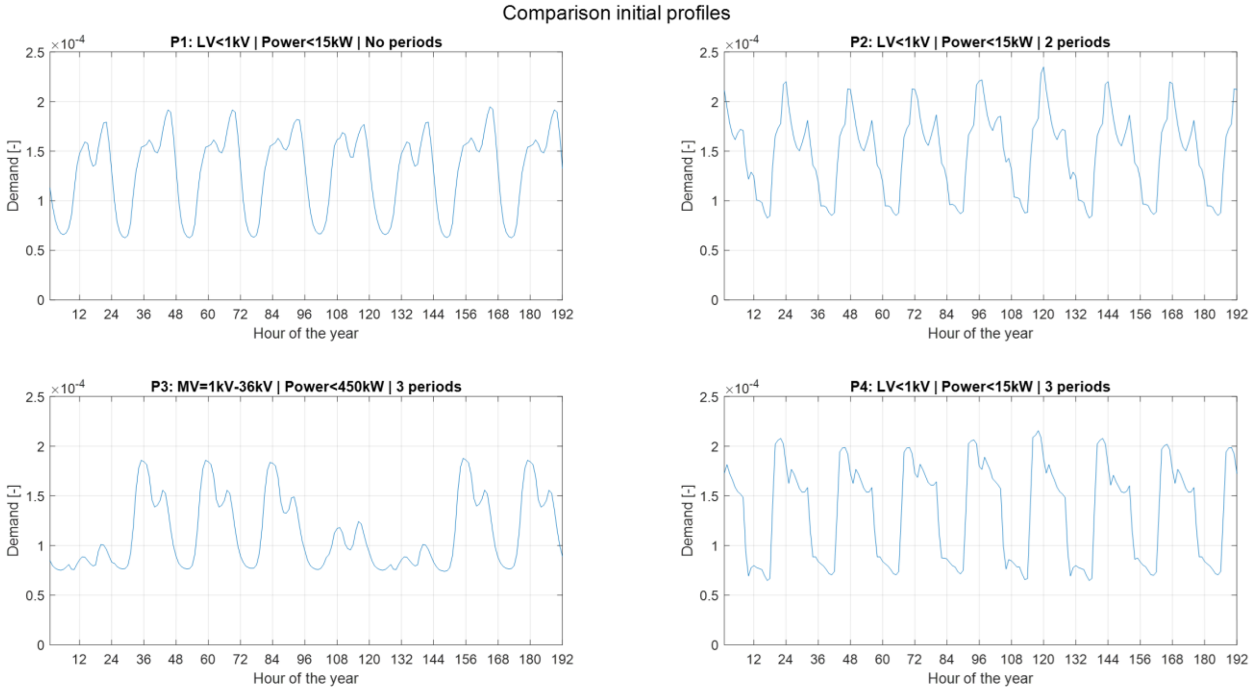


Figure 5 Representation of initial profiles according to the type of tariff

Total yearly load

The total yearly load has been extracted from the Spanish TSO, Red Eléctrica de España (REE). According to their website, the Spanish household's average electricity consumption is 3272 kWh per year [45]. However, this value is very variable and highly depends on the appliance configuration, like the space heating and air conditioner used, the cooking appliances, or the boiler.

Real demand of the system during the year

The last input needed is the real demand of the system for the whole year. This input is used to adapt the load profile to the electric network reality, intrinsically considering things like the weather variations, holidays, and other unexpected events.

Figure 6 [46] shows the profile that can be found on the Spanish TSO website. However, the maximum resolution given is daily resolution. This implies that the estimation of the curves extracted by this method will not include the intra-day variations of the real system demand.

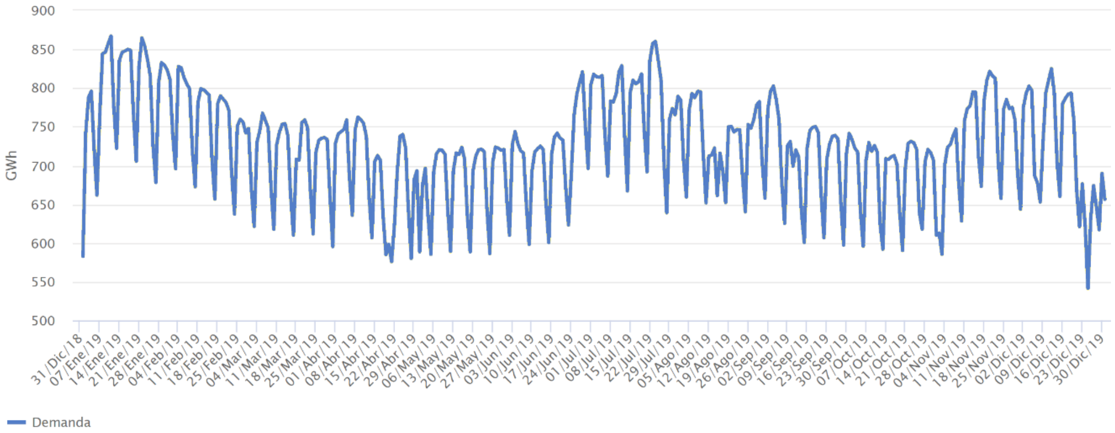


Figure 6 Evolution of the national electric system demand during 2019

Calculation

The initial profiles are modified according to the evolution of the "Real system" demand in comparison with the "Reference Demand" (expected demand given by the same document). This will intrinsically consider the unexpected consumption factors that affect the load, like the temperature or luminosity.

Figure 7 shows a comparison of the reference and real demand and the effects on the final profile.

- The parameters used to get the final profiles are the following:

$P^0_{m,d,h}$: Initial profile (obtained online [43]), for the month "m", day "d" and hour "h", representing the relative weight of each hour in the year.

$C^0_{m,d} = \sum_h P^0_{m,d,h}$: Sum of the initial profile coefficients for the 24 hours of the day

$H^0_{m,d,h} = P^0_{m,d,h}/C^0_{m,d}$: Weight of the hour "h" of the day "d" and month "m", in the total of the day "d" and month "m".

$M^{0m} = \sum_d C^0_{m,d} / \sum_m \sum_d C^0_{m,d}$: Relative weight of the month "m" in the year

$D_{m,d,h}$= Demand of the system in the hour "h" of the day "d" and the month "m" (only daily resolution available on the internet)

$DR_{m,d,h}$= Reference demand in the hour "h" of the day "d" and month "m", given together with the initial profiles (obtained online [43])

α, β, γ= Coefficients that depend on the contracted tariff, published yearly in [43].

$P^f_{m,d,h}$, $C^f_{m,d}$, $H^f_{m,d,h}$, M^f_m : Same definitions as the previous parameters but referred to final profiles.

The final profile will be obtained doing the following calculations:

- Adjustment of the energy in the hours with respect to the day

$$H^{1}_{m,d,h} = H^{0}_{m,d,h} * [1 + \alpha * ((\frac{D_{m,d,h}}{\sum_h D_{m,d,h}})/(\frac{DR_{m,d,h}}{\sum_h DR_{m,d,h}}) - 1)] \quad (1)$$

$$H^{f}_{m,d,h} = H^{1}_{m,d,h} / \sum_h H^{1}_{m,d,h} \quad (2)$$

Equations 1 and 2 were omitted due to the lack of hourly data on the system's real demand.

- Adjustment of the energy in the days with respect to the month

$$C^{1}_{m,d} = C^{0}_{m,d} * [1 + \beta * ((\frac{\sum_h D_{m,d,h}}{\sum_d \sum_h D_{m,d,h}})/(\frac{\sum_h DR_{m,d,h}}{\sum_d \sum_h DR_{m,d,h}}) - 1)] \quad (3)$$

$$C^{f}_{m,d} = C^{1}_{m,d} / \sum_d C^{1}_{m,d} \quad (4)$$

- Adjustment of the energy with respect to the year

$$M^{fm} = M^{0m} * [1 + \gamma * ((\frac{\sum_d \sum_h D_{m,d,h}}{\sum_d \sum_h DR_{m,d,h}}) - 1)] \quad (5)$$

Finally, to obtain the final profiles:

$$P^{f}_{m,d,h} = H^{f}_{m,d,h} * C^{f}_{m,d} * M^{f}_{m} \quad (6)$$

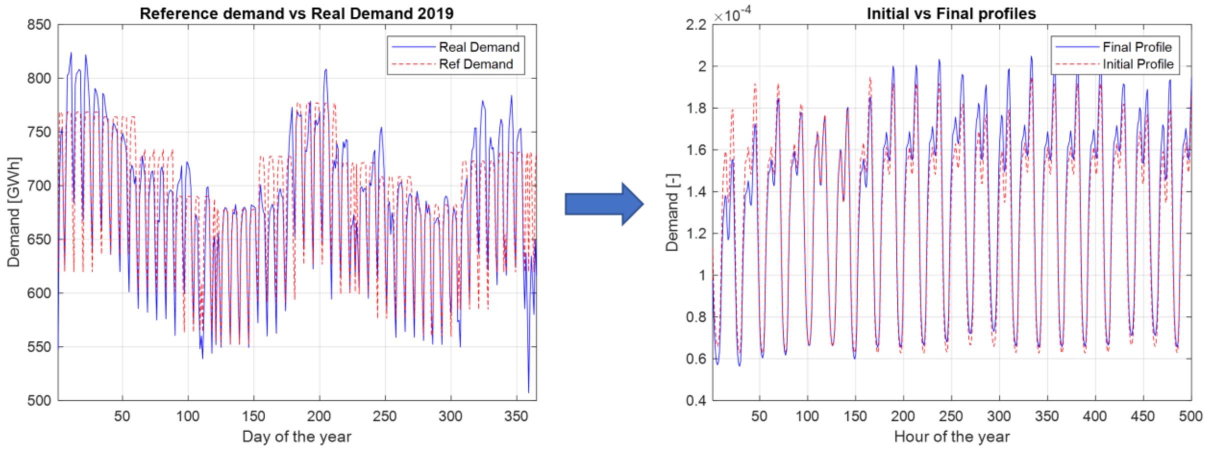


Figure 7 Comparison of reference and real demand (left) and initial and final load profiles (right)

Output

Once the final profile is obtained in Equation 6 (normalized), the multiplication by the household's total demand will give the final consumption profile hour by hour during all the year. Figure 8 shows the final load profile that can already be used as an input for *Prosumer*.

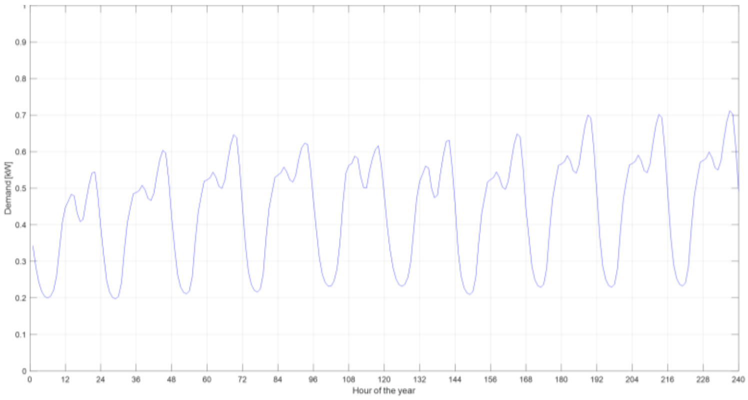


Figure 8 Final load profile

Advantages and disadvantages

The advantages of this method are:

- Simplicity, few inputs needed;
- Seasonal effects included in the initial profile;
- Real variations included in real demand of the system;
- Only depends on total consumption.

However, the method has some disadvantages that can alter the business case evaluation:

- Averaged profile not taking into account peaks of individual appliances and unpredictability of small communities loads;
- Hourly real demand of the system not publicly available, therefore intra-day variations are not taken into account.

3.4.2 Bottom-up model

The second approach taken to make the profile more realistic was to obtain data from the appliance consumption and then make a customizable model where the appliances in the house could be chosen.

Figure 9 shows the required inputs and output of this method. This model's inputs are the daily demand profile of each appliance, its daily consumption, and the desired dwelling configuration. With this approach, the output obtained will be the daily demand profile disaggregated by appliances.

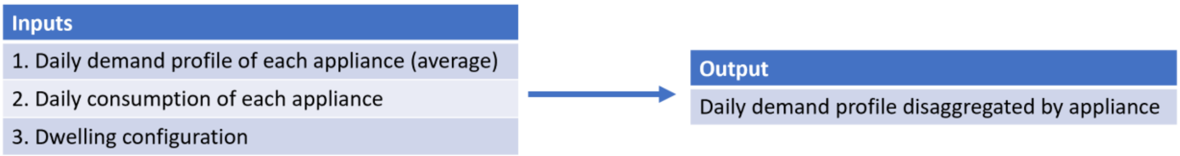


Figure 9 Required inputs and output of the Bottom-up model

Daily demand profile for each appliance

For each appliance, an average demand curve was extracted from "Atlas de la demanda eléctrica española" [47], an extensive document created in 1998 by the Spanish TSO. As only the normalized profile is being extracted, little differences are expected with the actual profiles. Figure 10 [47] shows two examples of the normalized profiles of the oven and washing machine.

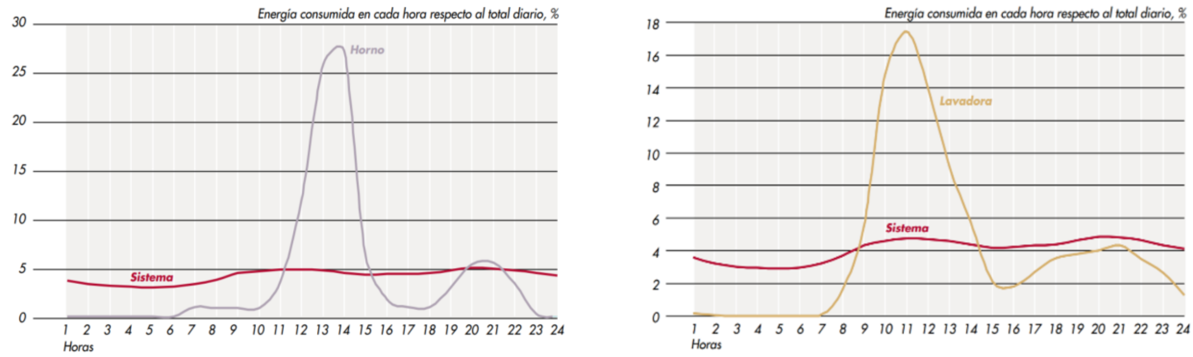


Figure 10 Normalized profile of the use of the oven (left) and the washing machine (right) during the day in Spanish households

Daily consumption of each appliance

Once the profiles are obtained, they need to be multiplied by the average daily consumption of each of them to create the average day's load profile. The consumption data was extracted from a statistical study [48] made in 2011 by IDAE (Institute for the Diversification and Saving of Energy), an institution depending on the ministry. The values can be seen in Table 5.

Table 5 Average yearly consumption of the main appliances in the model

Appliance	Average Consumption Per Dwelling [kWh/y]	Appliance	Average Consumption Per Dwelling [kWh/y]
Fridge	673	**Oven**	205
Freezer	614	**Microwave**	51
Washing Machine	252	**Tv**	255
Dish Washer	230	**Computer**	170
Dryer	260		

Dwelling configuration

The last step consists only of the selection of the appliances that want to be considered. As the load profile of a rural house pretends to be simulated, the appliances would have to be selected accordingly. Multiple ownership of some devices, like TV, can be taken into account in this model.

Output

For the selected appliances, the normalized profiles will be multiplied by the corresponding appliance consumption, giving as a result the average consumption profile of the device during the day. Summing the profile for all the household appliances, the average load of a dwelling is obtained, disaggregated by appliance. Their configurations can be modified to fit consumption data based on surveys. Figure 11 shows an example of the final output.

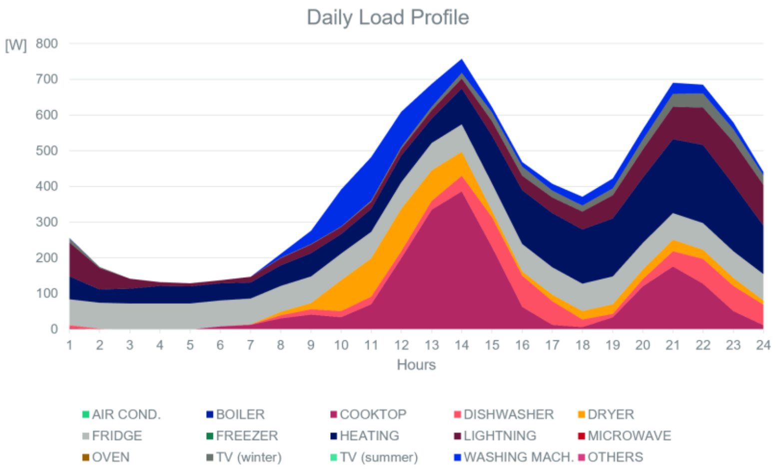


Figure 11 Example of daily load profile disaggregated by appliance

Advantages and disadvantages

The benefits of this model, in comparison with the previous, are:

- Disaggregated consumption by appliance;
- Possibility to customize the dwelling configuration and the consumption for each appliance.

The main disadvantages of this approach are:

- The model cannot be applied for individual or very small group of households because the consumption profiles are averaged;
- It only gets a 1-day load;
- Several different loads should be created for each season's typical day and weekend to take into account seasonal effects and holidays. Data may be complicated to find for all the seasons and even more for rural houses.

3.4.3 CREST (Centre for Renewable Energy Systems Technology) model

The third and last approach was the most realistic one, which was finally used as an input for the optimization software. Being the main disadvantage of the two previous methods that individual or small groups of households could not be simulated, a model to estimate single households' load demand was taken from the internet and developed for this study's specific needs.

A probabilistic demand model created by scientists from Loughborough University [49] was found and adapted to the needs of this study to forecast the load of the hypothetic community.

The original model, created with Visual Basic by Ian Richardson et al., is publicly available to download on the internet [50]. A detailed explanation of the original model will be done in the following paragraphs to understand the model's basis and its limitations.

Figure 12 shows the required inputs and the output of this method.

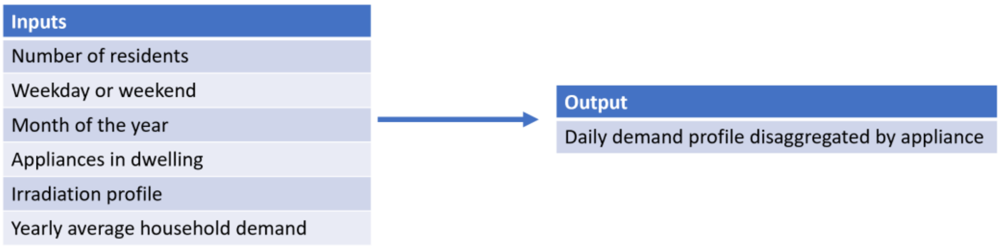


Figure 12 Required inputs and output of the original CREST model

The model base idea is that the pattern of electricity use in an individual household depends on the occupants' activities. Therefore, the model is based on a combination of patterns of active occupancy and daily activity profiles. Their study's final goal was to adequately represent the variability of individual household demand to study the implementation of demand-side management (DSM) strategies for local distribution networks.

Figure 13 [49] shows the schematic structure of the CREST model. The model uses the appliance as the base building block, creating the final dwelling demand profile from the sum of all the appliances (loads) present in the household. Therefore, it is a "bottom-up" model. The appliances are defined using statistics to describe their behavior, as the mean total annual energy demand, steady-state consumption, typical use cycles, etc. The model includes up to 33 appliances in each household, taking into account the possibility of multiple ownership (e.g., three TV in the same house). Each of the appliances is assigned a particular yearly demand, based on data from the UK Energy Saving Trust, representing a household in the UK's Eastern region, where the annual mean demand is 4358 kWh.

Therefore, every appliance in the model is considered to have two states: on and off (standby). The majority of the appliances are deemed to have a constant power demand when switched on, like the TV, oven, etc. However, some other devices, like the washing machine, have time-varying demands to represent better the reality of the different processes happening.

The next step of the development will consider each appliance's likelihood to be used at a specific moment. This likelihood will be naturally related to the dwelling's active occupancy, that is to say, the people who are at home and awake. In the model, it is represented as an integer that varies throughout the day in a pseudo-random way. The data used to represent it is derived from a Time Use Survey made in the UK, a survey of how people spend their time based on thousands of 1-day diaries recorded at a 10-minute resolution. This allows reflecting the behavior of real people in their day to day lives.

On the other hand, there are the so-called activity profiles, which can be seen on the left side of Figure 13. They are created as well from the Time Use Survey, which reflects the probability of the specified activity to take place as a function of time of day (e.g., cooking around mealtimes). The set of profiles includes variants to consider the active occupancy, thus assigning different probability profiles depending on the active people in the dwelling, from one to five (it is more probable that a particular appliance is used if there are more people in the house). Differentiation is also made between weekdays and weekends/holidays. These profiles are the same for all households.

The next step consists of linking all these day-to-day activities that take place inside the dwelling to the corresponding appliances used for those activities. For example, the oven and the stoves and microwave will be related to cooking, or the washing machine will be connected to the activity of laundry. By doing this, the varying likelihood of the appliance being used can be taken into account in a stochastic simulation. Therefore, detailed appliance usage statistics are not needed.

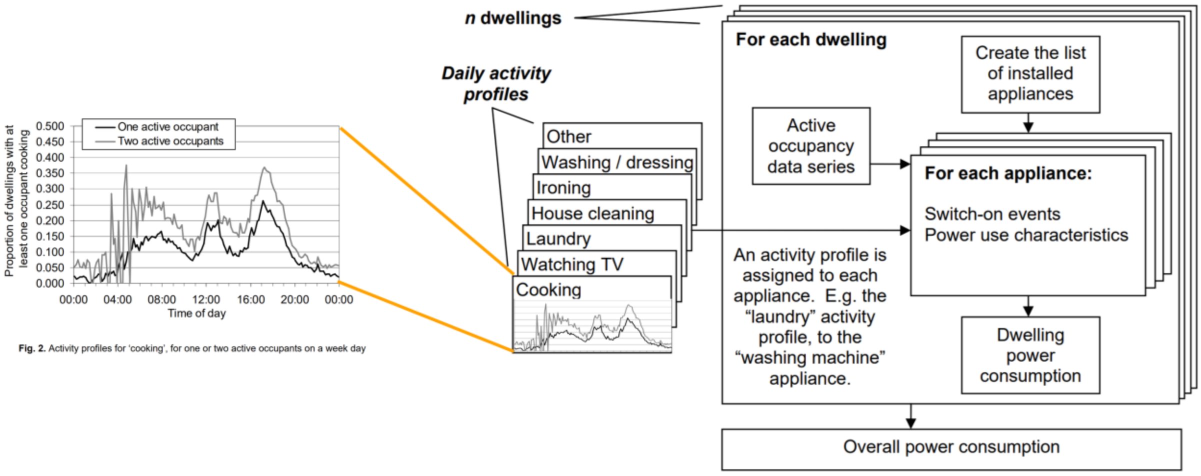


Figure 13 CREST model structure

There are some exceptions of appliances not linked to any activity profile. The first exception is when the use of the appliance is completely random (for example, a telephone). The second is when the appliance use is independent of the active occupancy. This may be the case for some cooling appliances like the fridge or freezer, which are always working independently of the people inside the household. To finish, the third exception is electric space heating or cooling appliances. Their use varies over the seasons and months, depending on the ambient temperature. The approach taken to model these appliances is to assign a coefficient representing the monthly temperature variation; thus, the probability of being used.

Using static activity profiles and keeping the number of active occupants as the main variable, the likelihood that appliances are used simultaneously can be represented. The probability of an appliance being used is increased non-linearly with the number of occupants. The correlated use of appliances is also taken into consideration with this methodology.

The load is represented at a 1-minute resolution. In a 365 days simulation, this means 525600 data points. This decision is a trade-off between the data volume and the curve smoothing of the demand, which has to contain useful information. For the detailed modeling of local distribution networks, it is important to be aware of high-frequency variations only observable in short resolutions.

As the model is based on individual appliances, reactive power consumption can also be adequately represented.

A brief summary of the structure of the model is presented in the following lines. An active occupancy data series is generated pseudo-randomly (random within predefined limitations), and a customized set of appliances are assigned, which at the same time are linked to an activity profile. This is combined with the activity profiles to determine when a switch on event occurs. When an appliance switch-on occurs, power use characteristics determine its electricity use. At the end of the calculation process, all the appliances' demands are summed up to obtain the final household demand. Figure 14 shows an example of the output.

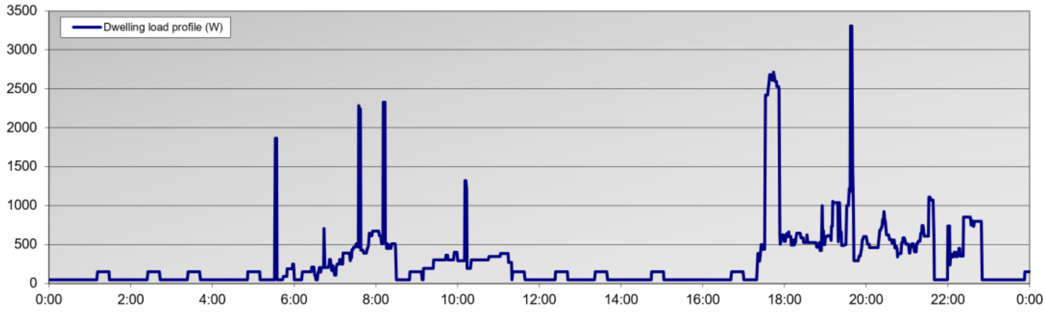


Figure 14 Final output of the original CREST model

The last thing is to understand how the switch-on events are modeled and when they occur. Figure 15 [49] shows the calculation process to determine switch-on events. The strategy to follow will be to select one appliance and make the simulation of that appliance for the whole day. In the first place, the activity profile is determined according to the appliance, the number of occupants at a specific time, and whether it is a weekend or not. Later on, the probability that any active occupant is engaged in the activity at a certain point in time is read. This probability is then multiplied by a calibration scalar, which is a number that determines the number of times that the appliance is used in a year so that over a huge number of simulations, the mean annual consumption of the appliance will be correct. As a result of the multiplication, the probability of switching on at that specific moment in time will be obtained. Lastly, this number is compared against a randomly generated number between 0 and 1, and a switch-on will occur if the random number is lower than the probability.

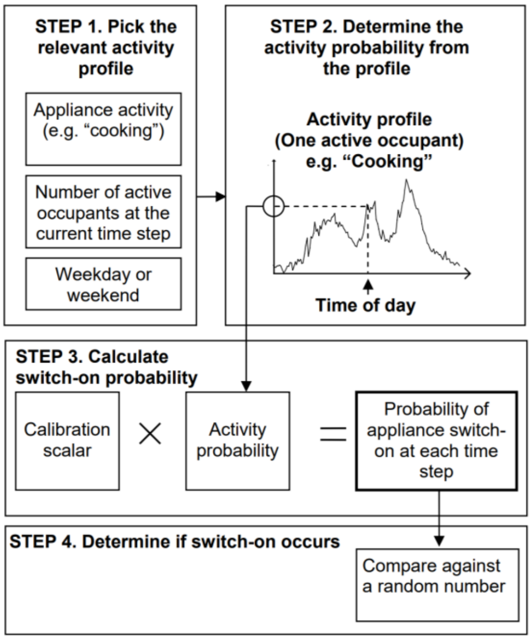


Figure 15 Switch-on event determination

Advantages and disadvantages

The main advantages of this model are:

- Minute resolution model that can be converted easily into the hour resolution needed;
- Possibility to simulate one independent household;
- It obtains the disaggregated consumption by appliance, which may be useful for similar studies;
- Pseudo-random realistic behavior of residents;
- Lighting model included that depends on the irradiation;
- Highly customizable.

However, some disadvantages remained that made them useless for this study:

- It can only obtain one day;
- Based on UK behavioral data;
- Does not include some important appliances, like air conditioning.

The code and the part of the data were modified to overcome the model limitations for its application in this study. The changes done on the original model are explained in the following sections.

Data format

First of all, the code, made on Visual Basic, was adapted to obtain the data in the format needed to input it in *Prosumer*, that is to say, an hour-resolution profile during the 365 days of the year.

To obtain the yearly load, the code was modified to run 365 times in a row and store all the 365 days simulated data. When doing these modifications, some considerations had to be made.

First of all, the code was modified to distinguish between weekdays and weekends. The people's behavior changes according to the day of the week, and the model uses different activity probability profiles depending on that.

Another important thing to change was the sun irradiation profile, used by the lighting model integrated into the load forecast model to simulate the electricity used for illumination at each minute of the day. As it was meant to run only for one day, the original model had a standard daily profile for each month of the year, so it was considering all the days in the same months exactly the same. Moreover, the profiles were taken from UK weather data, which is considerably different than the south of Europe. As now the objective is to simulate the whole year, the South of Spain's hourly irradiation profile was taken from PVGIS [35]. To take a representative irradiation year, the period between 2005 and 2016 was evaluated. The mean total irradiation of these years was calculated, and the year closest to that value (2009) was selected for the analysis. Finally, an interpolation was done using MATLAB to change the data from hourly to minute-resolution in order to use it as an input for the load forecast model.

Once the whole model's output result was obtained, with more than half a million data points due to the minute-resolution feature, an integration hour by hour was made to have a suitable input for *Prosumer*, the optimization software.

An extra feature was added in the code to visualize the consumption profile disaggregated by appliances. This additional feature can be used in the future to analyze which devices consume more in peak and valley hours and may be useful in Demand Side Management studies. Figure 16 and Figure 17 show an extract of one day of the demand profile, with the extra feature that allows the disaggregated visualization.

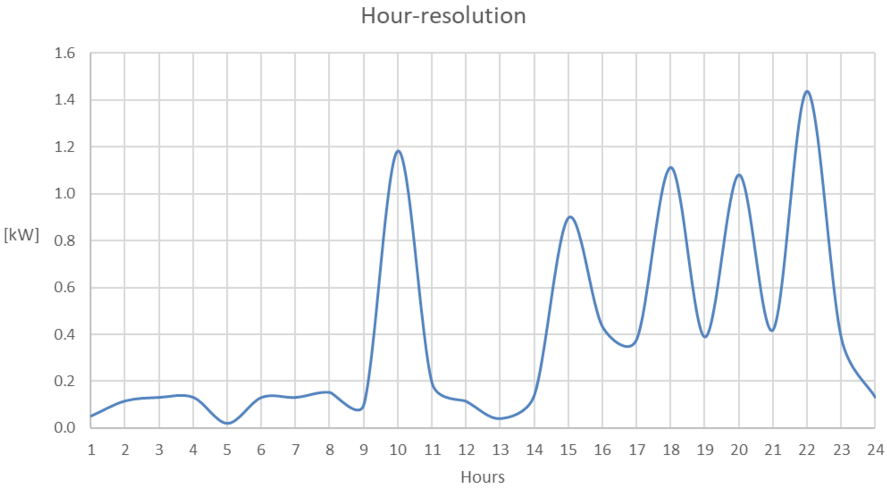


Figure 16 Extract of the final total output

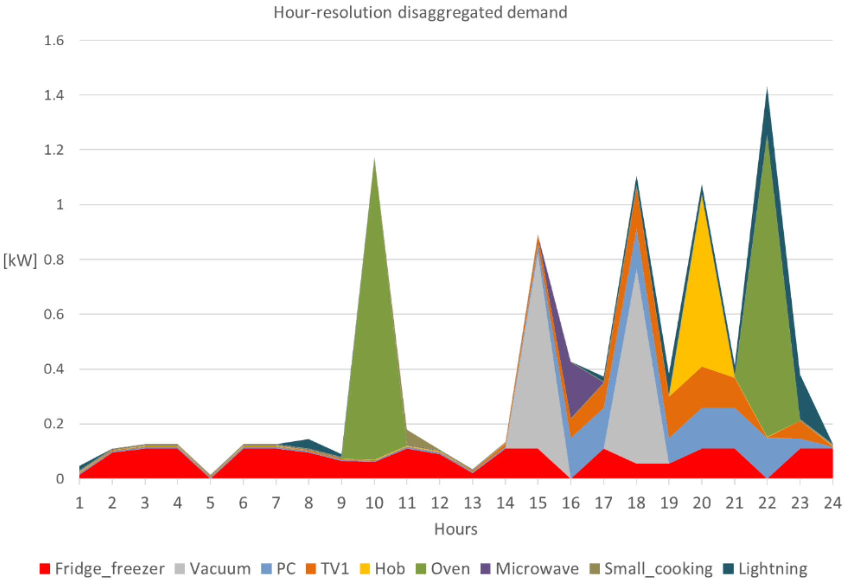


Figure 17 Extract of the disaggregated output by appliance

Data values

The second topic to address was modifying the model's database to adapt it to the consumers' behavior in the south of Spain. The electricity consumption was extracted again from the Spanish TSO and was set to 3270 kWh/y [45]. Presumably, this value would be lower in rural areas because electric heating and cooking appliances are not as common as in the rest of the country. However, as a first approach to the problem, the country's average consumption was used.

The average consumption of each appliance and the appliance ownership were extracted from two official documents (Spahousec I and II [48], [51], [52]). One of the source's drawbacks is that there is no discrimination between rural and urban dwellings in the ownership data. The values taken for some appliances can be seen in Table 6.

Table 6 Appliances average consumption and ownership in Spain

	Ownership [%]	Average Consumption Per Dwelling [kWh/y]
Fridge	99.7	673
Freezer	24.8	614
Washing Machine	99.6	252
Dish Washer	54.8	230
Dryer	34.9	260
Oven	77.1	205
Microwave	89.9	51
Tv	99.6	255
Computer	55.7	170

The space heating and cooling were also adapted to the weather conditions in Spain. As the ambient temperature during the year is quite different in both countries, the heating and cooling needs are completely different, up to the point that UK households do not need cooling. Therefore, the probability factors of using those appliances month by month were changed to match the Spanish case using Spahousec II [52] as a reference for the values to represent southern Spain's real climatic circumstances.

The original model reflects people's behavior by using the activity profiles, built using Time of Use Surveys performed in the UK, with 5 min resolution data from people habits. No similar study was found for Spain, which made it impossible to create customized activity profiles. However, the existing activity profiles for the UK were modified using the author's personal experience. The cooking activity profile was delayed 2 hours from the original one, and all the rest of the activities were delayed 1 hour.

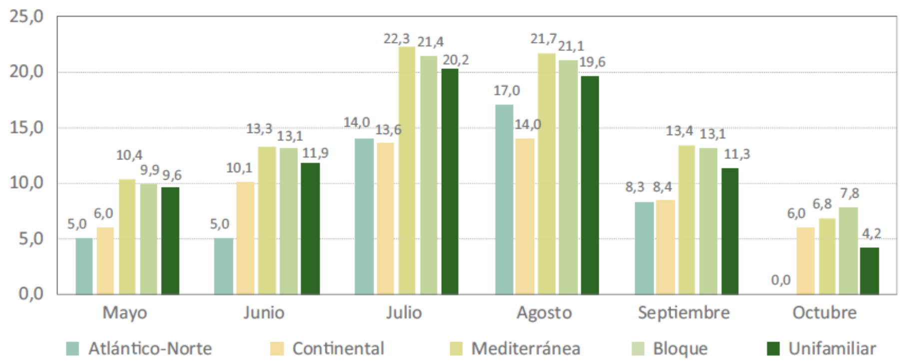
New appliances

As in the UK the need for cooling systems is much less, the original model was not equipped with air conditioning. However, in some regions of Spain, this appliance is very common. According to some studies from the National Institute of Statistics INE [53], around 35% of Spanish households are equipped with this appliance. Nonetheless, this proportion can change a lot depending on the region.

Another study from a real estate company [54] showed how in some cities in the south, like Sevilla, this proportion increased to 73.7%. In northern cities, however, this value can be almost as low as 0%. In Soria, for example, the value was just 0.2%. As the community is meant to be located in a place with high solar irradiation values, this appliance needs to be included in the model.

Therefore, the code was modified to include this appliance with a monthly dependent use. To characterize an appliance, several parameters are needed:

- The proportion of dwellings with this appliance: based on the studies mentioned above, was considered relatively high, up to 66%;
- Base cycles per year: according to Spahousec II, the base cycles per year was set to 90 days on average;
- Mean cycle length: extracted as well from Spahousec II, it was considered 240 minutes (4h);
- Mean cycle power: this value will depend on the specific model, which each dwelling will select depending on the size of the room to cool. For this study, a rather small Samsung model was selected [55], with 1030 W, enough to cool a 10 m^2 room, according to a study made by IDAE [56];
- Standby power: which was considered 0 W;
- Delay restart cycle: not applicable for this appliance;
- Occupancy dependency: Which in this case is applicable because it can only be activated when someone is active in the dwelling;
- Power factor: set to 0,8;
- Monthly dependent use (optional): In this case is compulsory because half of the year is not used, and the usage in summer months is also not homogeneous. The data was extracted again from the Spahousec II study. Figure 18 [52] shows the average number of days per month that the air conditioning is used for Spain's different regions.
- Specific load profile (optional): In this case, the load profile was considered homogeneous during all the cycles.



Base: 16.504.809 hogares.

Figure 18 Number of days per month (between May and October) that the air conditioning is used disaggregated by climatic area and type of household in Spain

Output

With all the modifications done, the inputs needed for the load forecast simulations are the number of residents of the household, the appliance configuration of the dwelling, the irradiance profile of the location during all the year, and the yearly average household demand. With these four inputs, the desired annual load profile with hour resolution will be obtained and ready to be input in *Prosumer* for the microgrid simulation.

As an optional feature, each appliance's individual consumption can be modified to fit specific cases where data is available.

Figure 19 shows the required inputs and outputs of the modified CREST model.

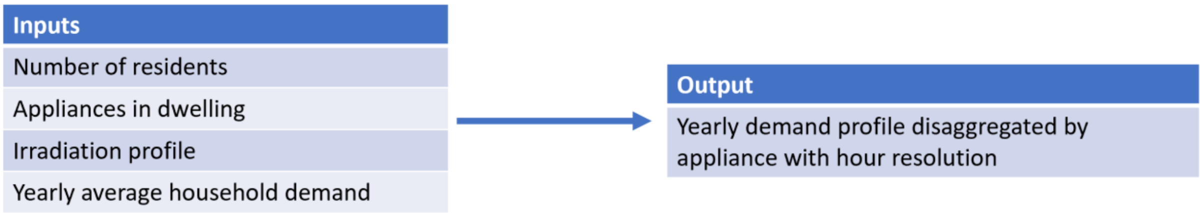


Figure 19 Required inputs and output of the modified CREST model

Final loads

The strategy followed to create the final loads was to run the simulation ten different times, making ten different yearly loads for ten individual households.

For the one house case, one of the loads was selected. The previous one-house load was picked for the two-house case and summed up with another of the individual loads obtained. The process continued until ten yearly loads were obtained, representing communities from one to ten households. Following this method, the simulation results' consistency can be guaranteed because to generate the load with n+1 house, the n case is used as a base. Therefore, the effect of adding one new house to the community can be observed. Figure 20 shows an extract of the first day of the year for 1, 4, 7, and 10 houses, with a minute and hour-resolution.

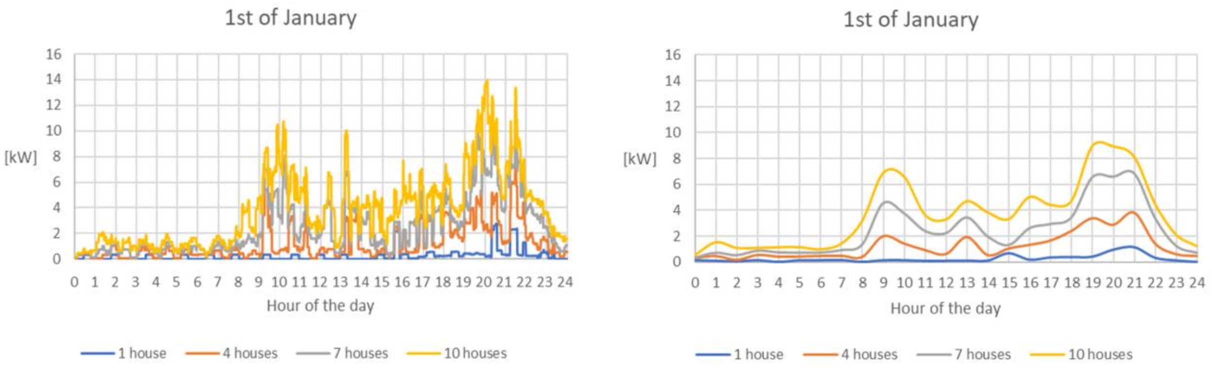


Figure 20 Minute-resolution loads (left) and hour-resolution loads (right) for the 1st of January

Result validation

As a first validation of the results given by the model, all the daily loads were averaged. Figure 21 shows the comparison between the profile obtained by the averaging of all the days of the simulation and the one provided by the Standard Profiles method explained above. As can be seen, it has the characteristic two peaks in the morning and evening, typical for domestic loads. The result is very similar to that given by the Standard Profiles method, which is a good indication.

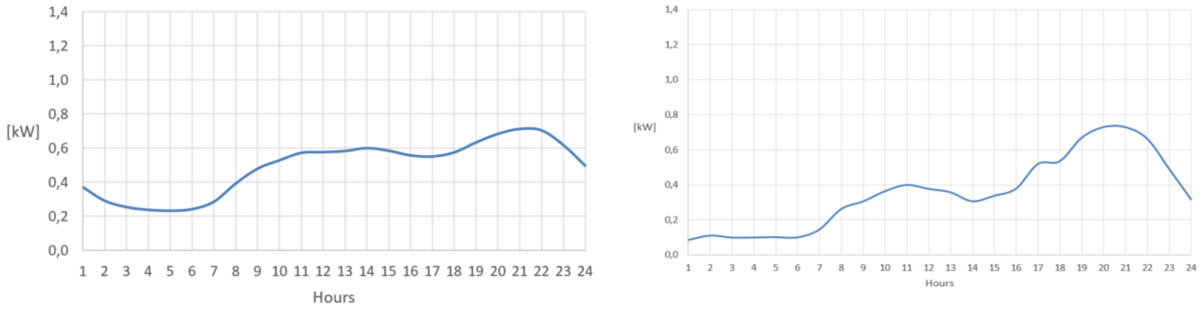


Figure 21 Daily load profile extracted from the Standard Profile Method (left) and the average of all the daily loads during a year for one household with CREST method (right)

4. Simulation results and analysis

In this chapter, the results of the simulations done with *Prosumer* will be exposed and discussed. Afterward, the microgrid project's total discounted cost will be computed, adding to the simulation results some extra costs not considered by *Prosumer*. Then, some research is going to be made on the costs of building, operating, and maintaining an MV line in Spanish territory. An approximate cost to make the comparison will be computed. Once the total costs of the two possibilities are obtained, the comparison of the two options will be made to verify which are the conditions that make the microgrid case positive and which are those that make the MV case more favorable. At the end of the chapter, some sensitivity analyses will be done in order to optimize the business case and check its strength.

4.1 Simulation results

In this section, the simulation results will be explained. Ten base cases were done, with the only difference between them being the load given as an input, representing communities from one to ten houses.

The section is divided into two parts:

- Asset size, where the optimal dimensions of the assets (battery and PV) will be given for the ten cases studied;
- Total discounted cost of the assets, where the discounted costs of the assets will be given, including the operation and maintenance costs.

4.1.1 Asset size

Prosumer optimizes the size of the assets in order to cover the demand at all times of the year. Therefore, it makes all the calculations knowing beforehand the load profile and also the production profile of the solar PV (see Methodology chapter for more information).

There is the possibility of a year with less solar PV production than expected or with a load higher than expected, both of which would lead to an energy shortage. Therefore, it has to be taken into account that an oversizing of the results is always needed to cover these two cases' uncertainties. An oversizing sensitivity study will be done at the end of the chapter to see how this influences the price and business case.

Battery energy and power

Figure 22 shows the optimized battery power for all the communities simulated. It can be seen how the necessary battery power evolves with the number of houses considered (and therefore with the number of inhabitants of the community). It can be noted how the power needed always increases as the number of houses increases. Except for the two first cases, the power follows a linear progression, installing approximately 3 kW extra power for every new house included in the simulation.

It can be observed how the two variables are directly proportional between them, which is not easy to interpret because the maximum peak power required by the community during all the year is not proportional to the number of houses. In other words, the community's maximum power need is not the sum of the maximum power need of each house separately because the power peaks of each household do not happen simultaneously. Figure 23 shows the highest peak power demanded by the communities for all the year

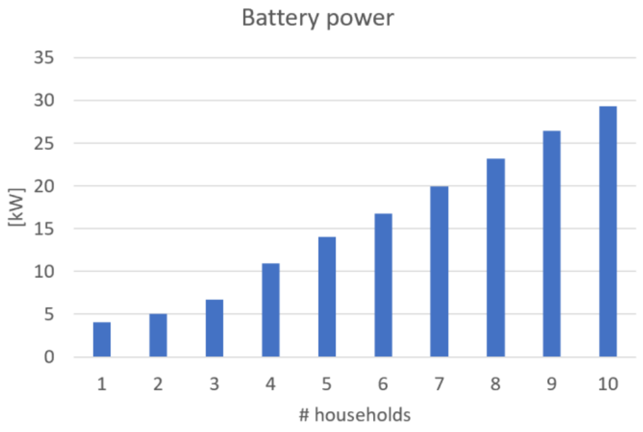


Figure 22 Optimized battery power for each of the base cases

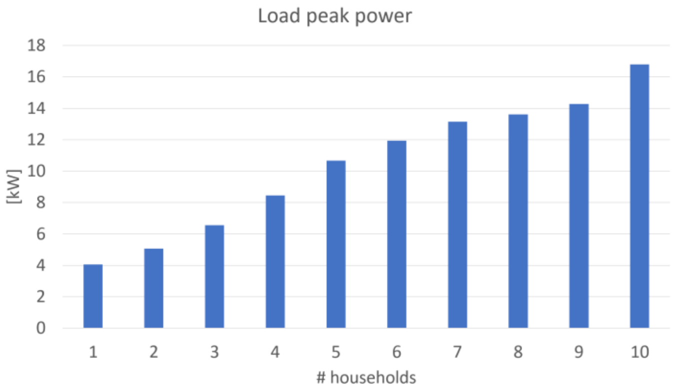


Figure 23 Peak power of each of the loads

To better understand the results, the *Prosumer* optimization process of the battery's power has to be explained. First of all, it must be noted the battery will be both charged (from PV) and discharged (to supply the load). Therefore, the battery power installed will be the maximum between the highest battery discharge rate and the highest battery charge rate.

The charge and discharge rate will be given by subtracting the demand profile and the PV power generation. Whenever the result is positive, the battery will be discharged, and when the result is negative, the battery will be charged. Not necessarily the highest power peak in demand will correspond to the highest discharge rate because there is the possibility that PV panels are supplying directly to the customers. In the same way, not necessarily the highest PV production time will be the highest charging rate. Moreover, the software can curtail the PV power production if the energy is not needed in the present or future days of the year or if the battery is fully charged.

In the end, the maximum of the charging function in absolute value will be chosen as the battery power installed.

Going back to the results, in Figure 22, it is shown that the values that follow the linear progression are those for three houses or more. These values always correspond to the maximum charging rate of the battery. As the charging rate depends on the PV installed, which is proportional (see results below), the maximum charging power for that cases will also be proportional.

For the cases with one and two houses, the trend is different because the maximum power corresponds to the maximum battery's discharge rate for all the year, which coincides with the community's maximum power demand.

Figure 24 shows the battery energy capacity installed for the ten cases. As in the power case, it follows a linear progression, and the two magnitudes are directly proportional between them. Approximately, *Prosumer* adds 25 kWh of energy capacity for each extra house of the simulation. This result is expected because the community's energy needs will be just the sum of each house's energy need separately. It is evident that the battery energy capacity has to be proportional to the number of houses.

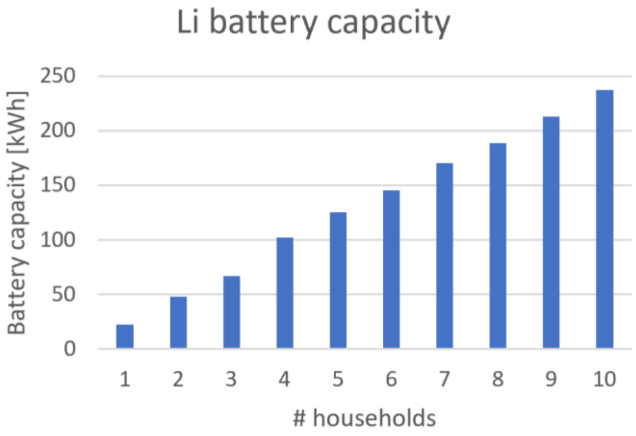


Figure 24 Optimized battery energy for each of the base cases

It is interesting to analyze also the energy to power ratio (E/P) of the batteries optimized by *Prosumer*. Dividing the battery energy capacity (kWh) by the power of the battery (kW), the duration (h) that the battery can be in operation, supplying energy at the rated power, is obtained. This value is also called the energy-to-power ratio, and it is often used as an indicative parameter to decide the most appropriate storage technology for the projects.

As shown in the previous chapter, this parameter is one of the inputs that should be set (as a range) in *Prosumer* for the storage. Lithium-ion batteries' default range in *Prosumer* was 0.25-4 hours because projects with the need for a battery with such energy to power proportion are usually favorable for this technology [57] [58].

The simulations were run in the first place with this default range. After checking the results, it was seen how the community's significant energy requirements obliged to install much more power than it was needed. Dividing the energies by the power for the ten cases, energy-to-power ratio equal to four hours, the upper limit, was always obtained. As a result, all the extra power installed, which was not needed by the community, substantially increased the microgrid price. These results may be an indicator that the technology used may not be the optimal one.

Finally, the decision was taken to run the simulations with a broader range, 0.25-10 hours, to check which was the project's real need. Those new simulations lead to the results already seen in Figure 22 and Figure 24. Figure 25 shows the E/P ratio of all the cases, obtained by dividing the optimum battery energy by the optimum power.

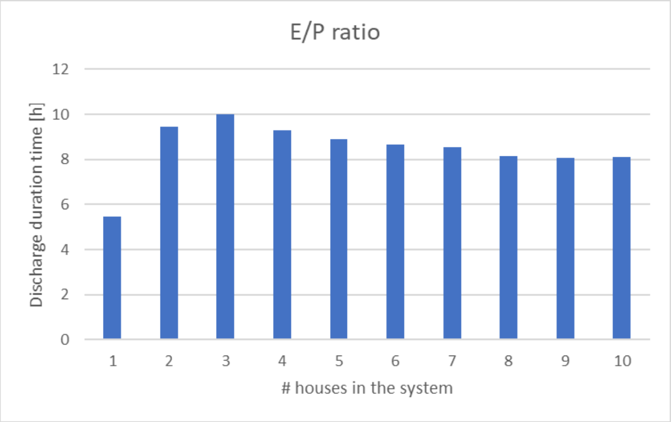


Figure 25 E/P ratio of the ten cases evaluated

As it can be seen in Figure 25, only in one of the cases, the one with three houses, the optimization took the ratio to the imposed limit of 10 hours, meaning that probably less battery power would be enough for that case. In all the other cases, the values were lower than 10 hours and always greater than 4 hours, the previous limiting value. This confirms the previous hypothesis that the E/P ratio was limiting the optimization of the batteries' power.

The mean value for the energy-to-power ratio of all the simulations is 8.5 hours. As stated before, this is an indicator that Lithium-Ion may not be the best-suited technology for this kind of application, which requires high amounts of energy to store and relatively low power in comparison. An alternative to that would be Vanadium Redox Flow batteries, which have a default range of 4-12 hours according to Laborelec[1], meaning that they can provide long duration discharges at nominal power (up to 12h in a row). Sensitivity studies will be done at the end of this chapter to compare both technologies.

Solar PV

Figure 26 shows the PV power installed for each of the ten base cases. Approximately, for each new house added 6 kW more are needed. The amount of PV installed is found to be directly proportional to the number of houses, which is expected. As stated in the case of battery energies, the community's energy needs are the sum of each of the houses' energy needs, making the solution proportional.

The PV energy supply is often curtailed during the year simulation. This happens because *Prosumer* knows precisely the weather conditions of the "future" (input of the hourly solar irradiation during all the year is given) and that extra energy generated is not needed to satisfy the future community's needs. This fact can also indicate that the PV is oversized to supply the community in the days with less irradiation in the year. At the end of this chapter, the possibility of adding an internal combustion engine to reduce this problem will be discussed.

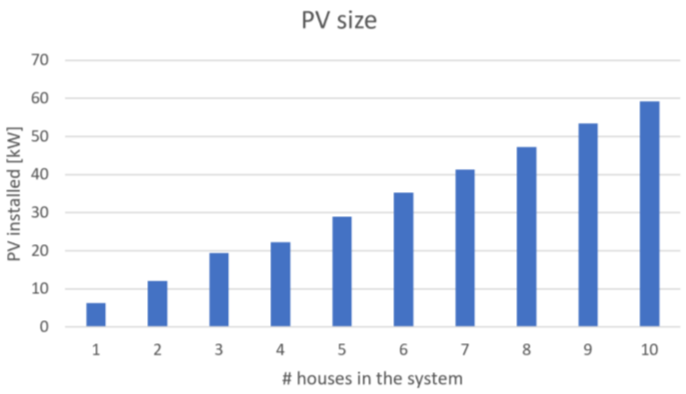


Figure 26 PV installed for each of the base cases

4.1.2 Total discounted cost of the assets

Once the assets' optimal size is known, the discounted cost calculation for the project was done by *Prosumer*, using the Methodology chapter's economic parameters. As a reminder, the WACC was set to 7.5%. The net present costs were computed:

---

[1] Information retrieved from a personal interview with a member of Laborelec [40]

$$NPV = C_0 + \frac{C_1}{1+WACC} + \frac{C_2}{(1+WACC)^2} + \cdots + \frac{C_{40}}{(1+WACC)^{40}} \qquad (7)$$

Where:

- NPV: Net Present Value of the project (also Total Discounted Costs)
- C_0: Initial investment (CAPEX 1st year)
- C_t: Costs in year t $C_t = O\&M + Asset\ Cost_t$
    - O&M: Operation and Maintenance costs of the assets. This value is constant through all the project
    - Asset cost: Reinstallation cost of the battery (every 10 years) and PV modules (every 30 years)
- WACC: Weighted Average Cost of Capital

After 40 years, at the end of the project lifetime, the assets' residual value is subtracted, using each of the assets' depreciation time.

Figure 27 shows the discounted costs for the assets of all the cases. For the smallest of the communities, with just one house, the assets' price during all the project lifetime is slightly over 25 k€. It can be noted that, for ten houses, this value ascends linearly to almost 250 k€. Again, it can be concluded that the system's price is directly proportional to the number of houses. Figure 28 shows the first-year operational expenditure (OPEX) and capital expenditure (CAPEX).

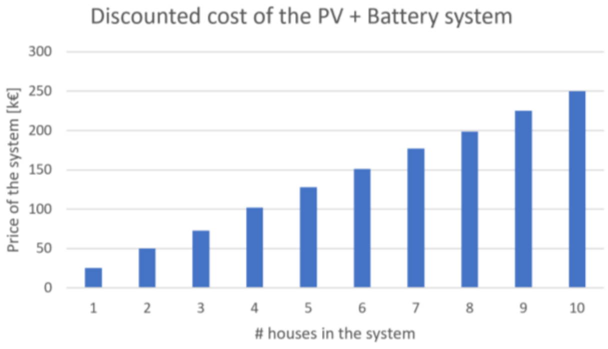


Figure 27 Total discounted costs of all the cases

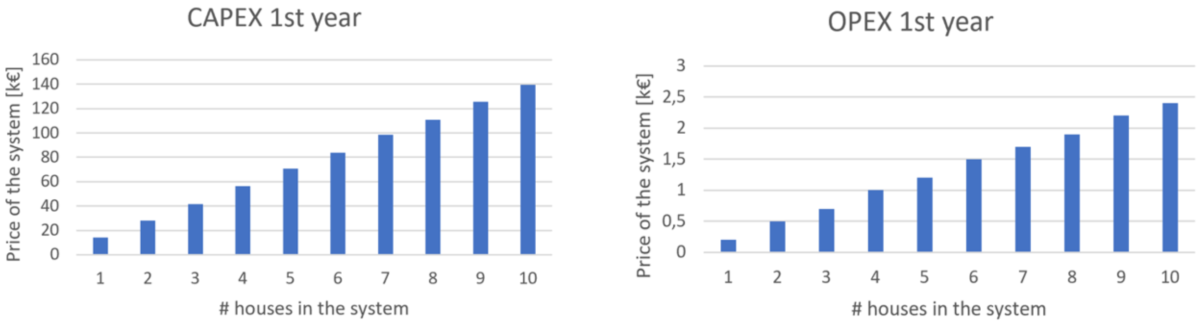


Figure 28 Initial investment and operational expenditure of the first year of the project

It is interesting to notice how the prices do not experience a scale effect. The price of adding an extra house to the simulation does not increase or decrease; it is constant and has an approximate value of 25 k€. This happens because the asset prices are always directly proportional to the number of houses.

4.2 Total microgrid costs

The total discounted cost of the generating and storage assets forming the microgrid has been computed until now. However, this is only a part of the full costs that involve the construction of such a system.

Taking as a reference a cost study made by NREL on 80 microgrid projects in the US [59], it can be concluded that the total price of the microgrid changes significantly depending on the market segment where the microgrid belongs and with its generating technologies. Figure 29 [59] shows the normalized costs for microgrids divided by market segment and level of complexity. It can be seen that community microgrids have, on average, the lowest costs.

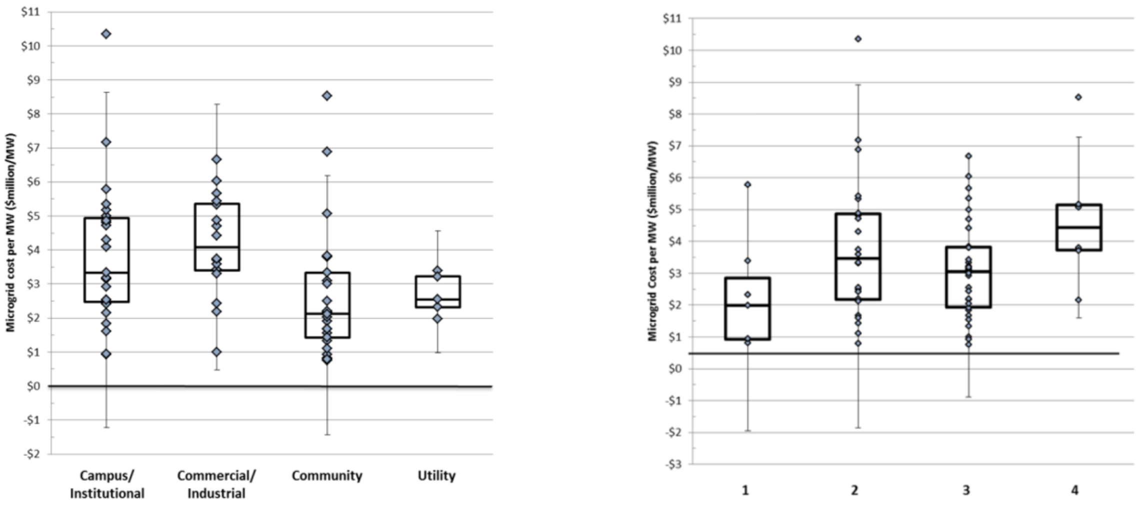


Figure 29 Box plot of normalized microgrid costs by market segment (left) and level of complexity (right)

The study also concluded that the capacity does not play an important role in determining the price per MW installed. Even if it is true that the costs per MW are usually lower for higher capacities, a smaller capacity does not necessarily imply an expensive microgrid. What usually plays a more critical role is the level of complexity of the microgrid, that is to say, the existence of microgrid controllers, renewable generators, energy storage, thermal assets, load management, and other factors that may increase the complexity of the case. According to their classification, the microgrid proposed in this study would fit into level 3 of complexity because it has a controller with renewable generation and storage.

The document also goes into more detail in the breakdown of the costs of community microgrids. Figure 30 [59] shows the average price per component.

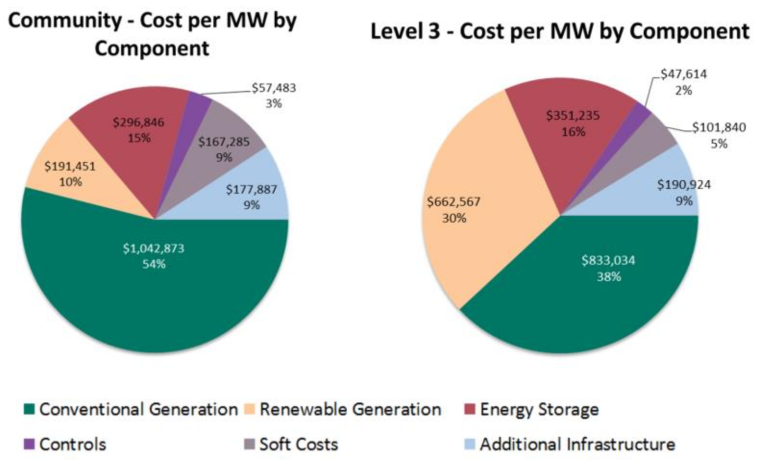


Figure 30 Costs by component for community microgrids

Prosumer discounted costs only take into account the generating and storage assets. According to the document, some extra costs still have to be considered to determine the total microgrid price.

The following extra costs will be discussed in the next paragraphs:

- Control system;
- soft costs;
- additional electric infrastructure;
- cost of the land.

Control system

The control system is a fundamental part of the microgrid. It is responsible for controlling the electricity flow in the microgrid, as well as the charging and discharging of the battery. According to NREL, the price for this equipment varies a lot from project to project. The cost per MW range from 6200 $/MW – 470000 $/MW, with a mean value of 155000 $/MW. However, as shown in Figure 30, the cost for community microgrids and level of complexity 3 is usually lower.

Figure 31 shows the discounted cost of the control system obtained for each base case, obtained by considering the costs as 3% of the total, as suggested by NREL statistics.

If the prices want to be compared with the NREL document, the 1st year CAPEX costs have to be used in the calculations. Considering the investment again on the controller as 3% of the initial investment, and dividing the controller's investment cost by the microgrid’s power, which is the sum of PV and battery power installed, the average price for this equipment is obtained, which is 60 €/kW (74000 $/MW). This value is inside NREL's range [65] but relatively high compared with other community and level 3 complexity microgrids. Therefore, the values can be considered somewhat conservative.

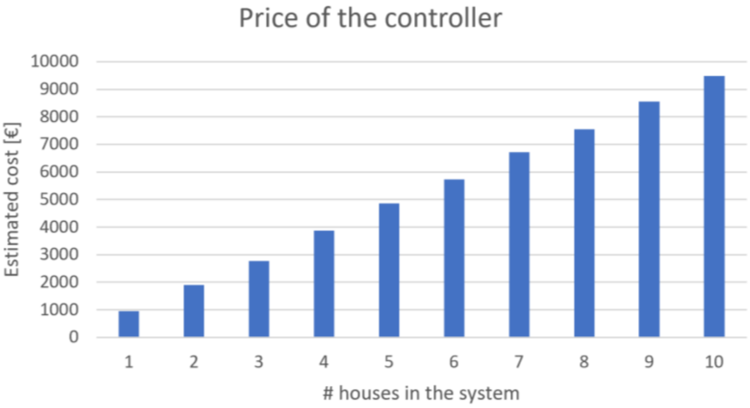


Figure 31 Discounted price of the controller for each of the base cases

Soft costs

The soft costs include engineering, construction, commissioning, and regulatory costs. This extra cost is very dependent on the specificities of each case. The NREL study obtained that it could range from 1%-75% of the projects' total costs. Again, Figure 30 will be taken as a reference. The value for the community microgrid, of 9%, was taken to be on the conservative side and consider the worst-case possible for the microgrid.

Following the same procedure as before, and using the initial investment to compare, a value of 181 €/kW (223000 $/MW) was obtained, which in this case is also inside the range predicted by NREL [59], but considerably high to be a community microgrid. However, according to the same NREL study, soft costs for projects under 1 MW can be higher. Therefore, these values will be used as well, keeping in mind that they are conservative.

Additional electric infrastructure

Additional electric infrastructure costs include all the expenses on tangible assets, excluding generation equipment. For example, cables, poles, circuit breakers, or distribution panels would be considered in this category. According to the NREL study [59], this value can range from 1%-38%. These assets' value is approximately the same as the soft costs for community microgrids, as can be seen in Figure 30. Therefore, additional electric infrastructure costs will be considered exactly the same as the soft costs, with a value of 181 €/kW of the microgrid.

Cost of the land

In addition to the previous extra costs included in the NREL document, the cost of the necessary land to install the PV system (and battery) was also explored.

The source used for calculating this value was a survey study made by the Spanish ministry of agriculture on agricultural land prices in different country regions [60]. In that study, it was found that the price per hectare ranged from 4 k€ for the cheapest region, Extremadura, up to 20k € for the most expensive one, Andalucía. The Canary Islands are an outlier, due to the limited amount of land, with a price of 87 k€/ha. The average price of land for all of Spain was found to be 10.2 k€/ha in the year 2018.

Regarding the space needed, it can be taken as a rule of thumb that for 1 MW of power, 2 hectares are required.

By multiplying the average price (10.2 k€/ha) by the spatial constraint (2 ha/MW) and the installed PV power, the land's estimated price for each case was obtained.

Variable costs, like taxes, have not been considered in the calculation. This is because small parcels of land with less than 1 ha are usually exempt from paying them. However, those taxes depend on each municipality and can change from place to place.

Figure 32 shows the results for the ten base cases. Compared with the other microgrid costs, the land cost is relatively low, representing barely 0.4% of the microgrid's total costs.

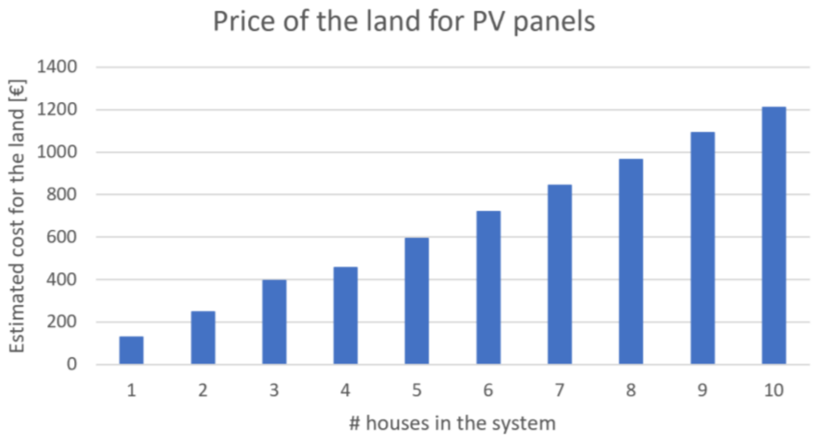


Figure 32 Estimated price of the land for the PV modules for each of the cases

Total costs

With all the extra costs computed, an estimation of the total discounted costs for the ten cases can be done. Figure 33 shows the total cost disaggregated by categories. The total discounted cost will be the sum of all the assets' cost, the soft costs, the additional infrastructure costs, the control system, and the land's cost.

From the results, it can be concluded that the total discounted cost of the 40 years project for one house (with three people living) is approximately 32 k€ (6 kW PV and 4 kW/22 kWh battery). The number of dwellings is directly proportional to the project's total cost, being around 32 k€ the price for every added house in the system. For a system with ten houses (approximately 30 people), the price is slightly less than 320 k€ (59 kW PV and 29 kW/ 238 kWh battery).

$$\boldsymbol{Total\ discounted\ cost} = Storage + PV + Soft\ costs + Add.infrastructure + Control\ sys. + Land$$

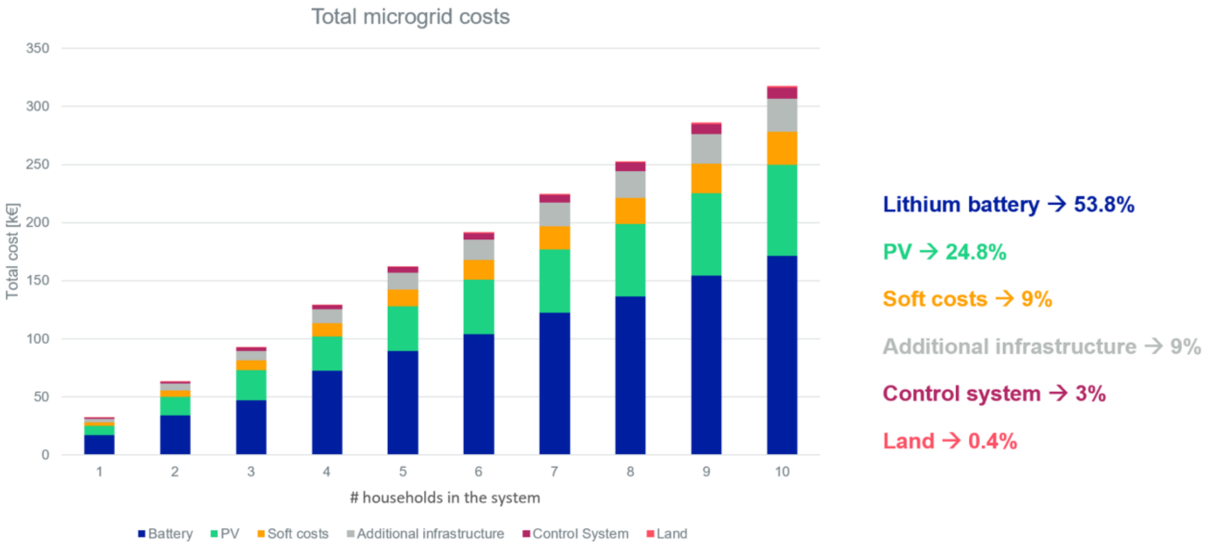


Figure 33 Total microgrid costs disaggregated by category

To obtain the total discounted costs per MW for the microgrid project, the same procedure as NREL [59] will be applied. The costs will be divided by the sum of the solar PV power installed and the microgrid battery power. If this is done for the ten cases, an average of 3.6 million €/MW is obtained.

However, this is still the discounted cost for the 40-year project. If only the first year's costs are considered, to have a fair comparison with the NREL document [59], a value of 2 million €/MW or 2.5 million $/MW is obtained. Compared with Figure 29, it can be noted how for both Community and Level 3 complexity categories, the value is near the average. Compared with the Community category, it is slightly more expensive than the average, but looking at the Level 3 category is slightly cheaper than the average. This is an indicator that the costs are in-line with the other registered microgrids in the NREL database.

These small price differences can be attributed to several factors. It may be due to the difference in asset price between the US and Europe. Another possible option is the exceptionally small systems considered in this study (from 10 kW to 90 kW), which may increase the price.

The storage is responsible for 54% of the total costs, and solar PV for 25%. Soft costs and additional infrastructure were forced to represent 9%, as well as the control system, which accounts for 3% of the total costs. The cost of land is almost negligible, representing less than 0.4 % of the total.

Once the total microgrid costs have been obtained, the comparison with rebuilding the MV line has to be done.

4.3 MV line cost

In this section, the MV line cost will be computed. It is crucial to notice that, unlike microgrid costs, MV line cost will depend on the number of kilometers to be built.

In Spain, electricity distribution is a regulated activity. This activity constitutes a natural monopoly because it does not make sense to build distribution lines where another distributor has already done so. However, by paying a distribution fee, any electricity marketer can use them to sell electricity.

As a regulated activity, a regulator supervises such companies' costs and expenditures to ensure a system with the security of supply and high power quality. The distribution companies have the function of distributing the electrical energy, that is to say, expanding, maintaining, and operating the distribution networks.

Therefore, they are responsible for presenting their investment plans annually to the different regions' governments to ensure a high-quality service for all the customers and expand the network to ensure everyone is supplied. In such a context, the Spanish regulator periodically establishes the reference prices for all the distribution assets to avoid frauds and over costs from the distributors. All the costs presented by the distribution companies must be in a range of ±10% of the prices stipulated in the document.

This document has been used in order to determine the MV line cost and compare it against the microgrid case [7]. For the sake of simplicity, only the cost of the MV lines and the MV/LV transformer will be considered. The costs of the electrical protection equipment will be omitted.

Several values can be found in the document for the MV lines, depending on their voltage range, the cable section, and the type of circuit (simple, double, triple circuit; underground or overhead). To reduce the number of cases, the four lower voltage ranges were selected. Among all the cable sections, the smallest one was always chosen to have the lowest price possible (between 0 and 56 mm^2). Following the same philosophy, the cheapest type of circuit was selected, that is to say, a simple overhead circuit. The investment values and its yearly operation and maintenance costs per kilometer, extracted from the document, can be seen in Table 7.

Similarly, for the transformer, the cheapest one was selected. Among all the possible locations (indoor, outdoor, etc.), the cheapest one to build and maintain was the outdoor location. In the same way, the lowest power rating of all, of 15 kVA, was selected. Due to the little differences in price, the same transformer has been considered for the four voltage ranges, with the parameters on Table 8.

Table 7 Investment and O&M costs per km for MV lines.

Voltage Range	Investment [€/km]	O&M [€/km]
1 kV ≤ U ≤ 12 kV	46814	486
12 kV ≤ U ≤ 17.5 kV	52666	547
17.5 kV ≤ U ≤ 24 kV	58518	607
24 kV ≤ U ≤ 36 kV	67296	698

Table 8 Investment and O&M costs for an outdoor 15 kVA transformer

Apparent Power [kVA]	Investment [€]	O&M [€]
15	13269	304

Once these values have been obtained, the project's value for the 40 years lifetime can already be computed (according to the document, this is the lifetime of these assets). The total discounted costs of the MV line project will be computed multiplying the discounted costs of the MV line per kilometer by the required length plus the discounted cost of the transformer. Therefore:

$$Total\ disc\ cost = Disc\ cost\ of\ MV\ line/km * \#\ km + Disc\ cost\ transformer \quad (8)$$

Where:

- Discounted cost of the line per km and the discounted costs for the transformer are going to be calculated using the same formula used before:

$$Disc\ Cost = C_0 + \frac{C_1}{1+WACC} + \frac{C_2}{(1+WACC)^2} + \cdots + \frac{C_{40}}{(1+WACC)^{40}} \quad (7)$$

Where:

- C_0 is the investment value in Table 7 and Table 8.
- C_t is the O&M costs in Table 7 and Table 8., which are constant during the 40 years
- WACC is set to 7.5% to have a fair comparison with the microgrid case

Applying this formula, the discounted costs in Table 9 were obtained.

The remaining factor is the length of the MV line, which will be one of the variables used to make the comparison, together with the number of houses in the system.

As a base case, the cheapest of the MV lines, with voltages between 1 and 12 kV, will be used. Sensitivity analyses will be done with the rest of the lines.

Table 9 Discounted cost of MV line and transformer for a 40-year project

Asset	Discounted Cost [40 Years]
MV Line: 1 kV ≤ U ≤ 12 kV	52960 €/km
MV Line: 12 kV ≤ U ≤ 17.5 kV	59583 €/km
MV Line: 17.5 kV ≤ U ≤ 24 kV	66194 €/km
MV Line: 24 kV ≤ U ≤ 36 kV	76123 €/km
Transformer Center 15 kVA	17113 €

4.4 Microgrid vs. MV lines

This section aims to identify the threshold distances and load that makes the microgrid business case favorable compared to the MV line reconstruction.

These two variables have been selected as the most representative ones for the business case.

On the first hand, the distance from the community to the primary grid is crucial because the costs of reconstructing the MV lines depend primarily on this value. The further a community is from the main grid, the more expensive it will be to build an MV line to supply electricity to it.

On the other hand, the amount of energy needed per year is also important. It has been shown how the costs of building the microgrids depend proportionally on the number of houses of the system (i.e., the number of people in the community). The more people living, the more energy will be consumed in the year, leading to a more expensive microgrid system. However, the MV line costs do not change so drastically with the size of the community. Therefore, the bigger a community is, the more favorable it will be to build an MV line to supply it.

In the previous sections, the computation of the total discounted costs for both projects has been explained. Equaling these costs, the threshold distance from which it will be more favorable to build a microgrid can be obtained. It will be computed by subtracting the microgrid and the transformer's discounted costs and dividing the result by the discounted of the MV line per kilometer.

4.4.1 Base case

The base case compares the microgrid costs with the cheapest of the lines (1-12 kV). Figure 34 shows the threshold distances that make microgrid case economically better than replacing the MV line.

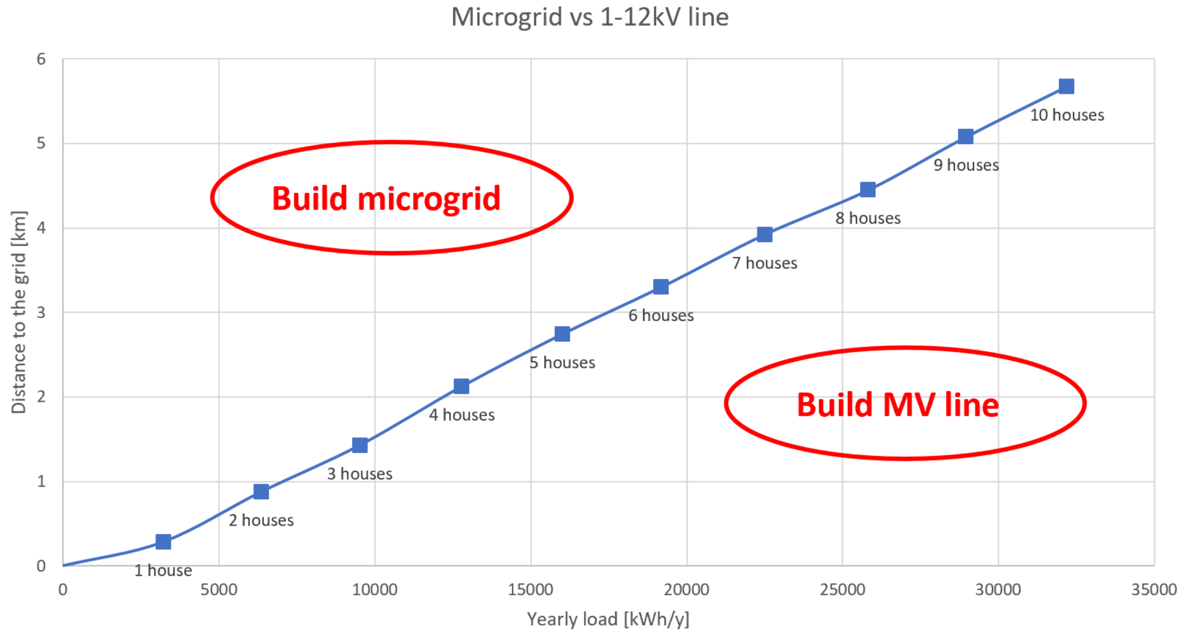


Figure 34 Threshold distances that make microgrid case more favorable against a 1-12 kV line

As shown in the figure, for a single dwelling (approx. 3 people and 3200 kWh/year load) that is more than 280m away from the main grid, it would be favorable to build a microgrid instead of an MV line. As the number of houses (and people) increases, the distance goes to higher values. For ten houses (or 30 people) community, the threshold distance that would make a favorable microgrid business case would be 5.6 km.

As a rule of thumb, the number of feasible meters to build per each customer will be given by the line's slope. This slope is approximately 187 m/customer, which means that for every customer to supply, up to 187 meters of MV line can be built. If more length per customer has to be built, it is economically better to build a microgrid.

4.4.2 Sensitivity analyses

In the next paragraphs, sensitivity analyses will be done to the most critical parameters of the comparison. The base case shown above is going to be always kept for comparison.

This analysis comprises the sensitivity on:

- MV line voltages;
- Oversizing;

- Weather uncertainties;
- Load uncertainties;
- Battery lifetime;
- Battery price and technology;
- Addition of diesel.

MV line voltage

The first sensitivity explored was regarding the voltage of the MV line. For the base case, the lowest voltage was selected. However, if distances are long, higher voltages may be needed. Using the values in Table 9, threshold distances can be computed for all the lines. Figure 35 shows the results of the sensitivity analysis of different voltage lines. It can be noted that the higher the voltage is, the lower the threshold distances are. This is evident because higher voltage lines lead to higher costs, making the microgrid case more profitable. Furthermore, the differences in the threshold distances increase with the number of dwellings conforming to the community. For the most expensive case considered, the 24-36 kV line, the threshold distance is always 30% closer to the main grid.

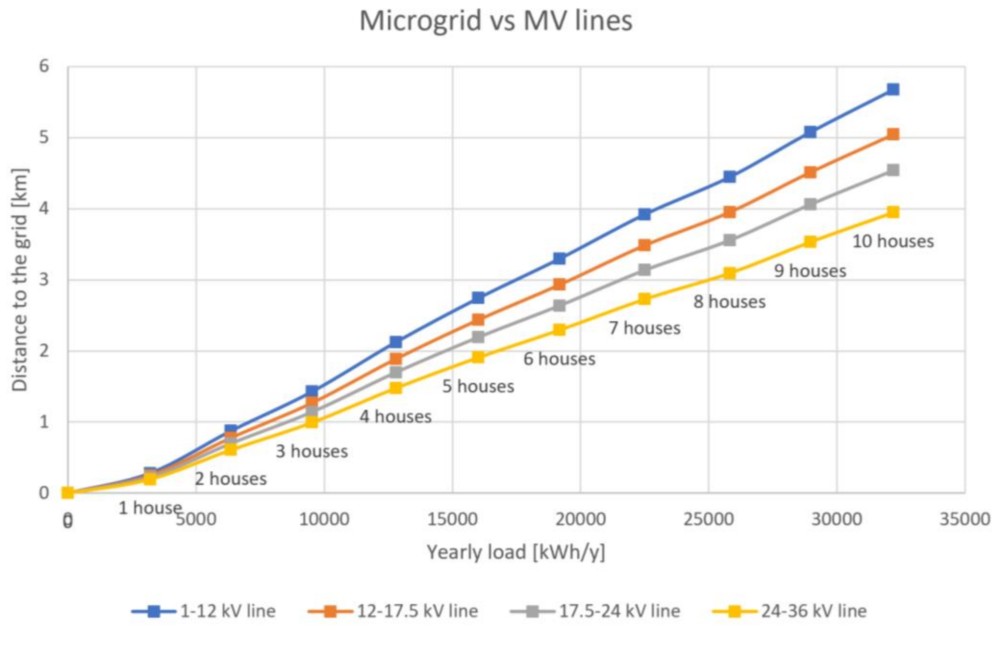


Figure 35 Sensitivity analysis of different voltage lines

Oversizing

The next sensitivity to be checked was the asset oversizing. As explained in the previous chapter, *Prosumer*, the optimization software, optimizes the asset size with perfect knowledge of the future load and weather variations. Therefore, the optimization is done to be able to supply the electricity in all the hours of the specific year. However, the same configuration would not be able to do so in a year with worse climatic conditions or a higher load.

Therefore, the assets in the microgrid need to be oversized to increase the security of supply. All the costs of the microgrids are going to be considered proportional to the oversizing rate. For PV and Li-ion batteries, it is safe to assume that building a certain extra proportion will lead to a change in the price of the same order. For the other components of the total microgrid costs, which are soft costs, additional infrastructure costs, control system costs, and land costs, the same will be applied.

Thus, total microgrid costs will increase at the same rate as the oversizing being considered. Sample oversizing of 25%, 50%, 75%, and 100% were done. Figure 36 shows the results for the oversizing sensitivity. It can be observed that for the most extreme oversizing, where the asset size is doubled, the threshold distances are slightly more than double. This makes sense because the transformer's cost, which is subtracted from the microgrid's cost in the distance calculation, does not double with the oversizing but is kept exactly the same.

Following this analysis, sensitivities on the load and weather conditions will be explored to understand the oversizing required.

If a back-up generator is considered in the system to supply in hours with deficient electricity reserves, the oversizing considered can be even lower.

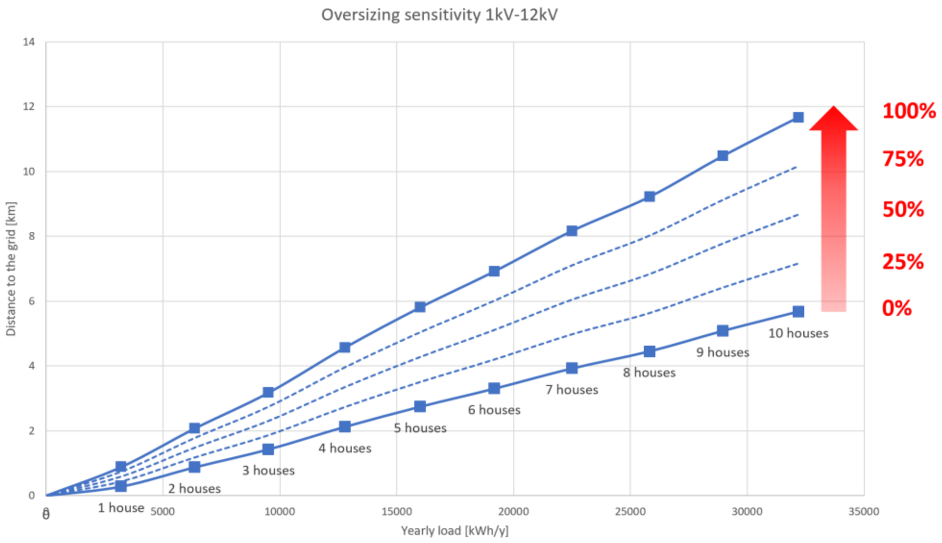


Figure 36 Oversizing sensitivity of microgrid assets

Weather uncertainty

The first of the two oversizing-related parameters checked was the uncertainty of the weather conditions during the year. The microgrid's energy production relies completely on solar PV, that is to say, the solar irradiation reaching the panels during the year.

All the data regarding the solar irradiation was extracted from PVGIS [35] for the coordinates [37.866; -4.529] (south of Spain).

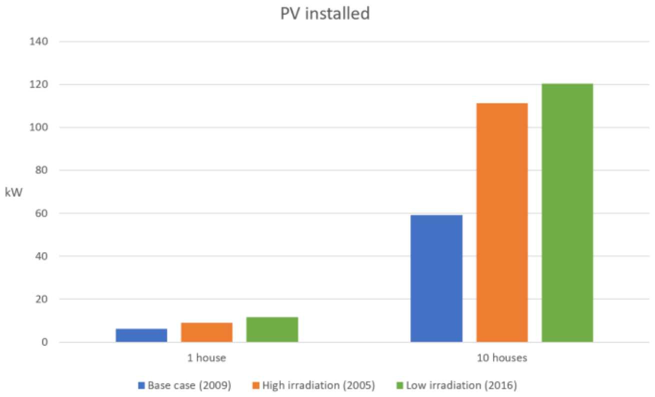


Figure 37 Installed PV for each of the cases for 1 and 10 houses communities

In the base case, the irradiation of the year 2009 was considered because it had the yearly value closest to the average of the period 2005-2016, thus being the most representative year. The daily average on the inclined plane (34°) for that year was 4.47 kWh/m^2/day.

For the sensitivity study, the two extreme cases of the period 2005-2016 were taken. The year with the highest daily average irradiation was 2005, with a 4.77 kWh/m2/day value, 6.7% higher than in the base case. The lowest daily average irradiation belonged to 2016, with a value of 4.15 kWh/m^2/day, 7.2% lower than the base case.

Figure 37 shows the installed PV in the microgrid for one and ten houses depending on the irradiation. Figure 38 shows the battery power and battery energy capacities installed for one and ten houses depending on the irradiation.

For the year with higher irradiation, 2005, Prosumer increased the PV installed substantially. For the 1-house community, a 44% increase was observed. For the case with ten houses, the increment seen was even larger, reaching 88%, as can be seen in Figure 37. The battery capacity and size, however, was dramatically decreased. For the 1-house community, the power remained the same, but the energy capacity was reduced a 36%. For the biggest community, with ten houses, this percentage increased to more than 55%. The power was also reduced a 43% as can be seen in Figure 38.

All these values show that, for a higher irradiation year, the strategy to follow would be to increase the PV installed, to take profit from the higher irradiation, and reduce the storage size and power, which is the most expensive part of the investment. All these changes lead to a cost reduction of the assets of 10% approximately. Figure 39 shows the asset price for one and ten houses depending on the irradiation.

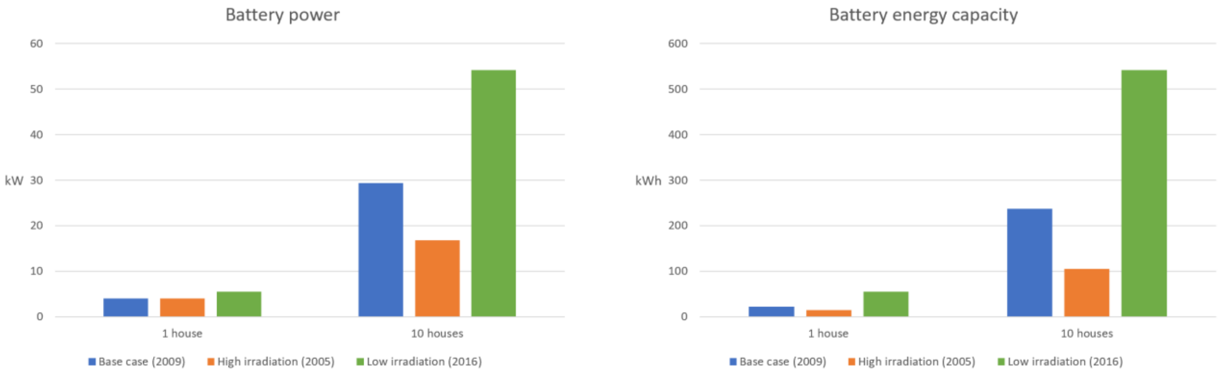


Figure 38 Installed battery power and energy capacities for each of the cases for 1 and 10 houses

For the year with lower irradiation, 2016, Prosumer increased both the PV installed and the battery power and energy capacity. For the one house community, the PV installed was increased an 86%. This increase was even higher for the biggest community, up to 103%, as can be seen in Figure 37.

The battery power was also increased, 36% in the smallest community and 85% in the biggest one. The energy capacity was the parameter that experienced the most significant increases with respect to the base case, 150% for the one house community and 128% for the ten-house community, as can be seen in Figure 38.

Gathering all the values in the previous paragraph and comparing them with the base case, it can be seen that the optimization for years with substantially lower irradiances lead to an increase in the PV size installed, together with a strong increase in the battery power and energy capacity. All these changes lead to an average increase in the cost of the microgrid assets of 112%, as can be seen in Figure 39.

From the results, it can be seen that, for similar variations in the average daily irradiation (±7%), the effects on the costs of having a higher irradiation year are much less than the effects of having a low irradiation year. For the first case, only a decrease of 10% of the assets price is observed, meanwhile for the second case, an increase greater than 100% is observed. This difference is mainly due to the amount of storage that has to be installed for the case with the lowest irradiation, which has to be high enough to supply electricity in the weeks of the year with less PV production.

Figure 39 Asset price for each of the cases for 1 and 10 houses

The progression of the function of the assets' costs with respect to the amount of irradiation seems to be a negative exponential function, being very high and steep for low irradiations and becoming lower and flatter.

Figure 40 shows the effect of these price changes on the business case's threshold distances, considering that all the extra costs are proportional to the costs of the assets. For the high irradiation case (around 7% higher), it can be seen that the threshold distance decreases by 12%. For the low irradiation case (around 7% lower), the threshold distance for the biggest community case increases by 119%.

It can then be concluded that having constant irradiation during all the years of duration of the project is massively important to make the business case positive. An alternative would be, as discussed previously, the addition of an internal combustion engine as a back-up generator for those years with lower irradiation.

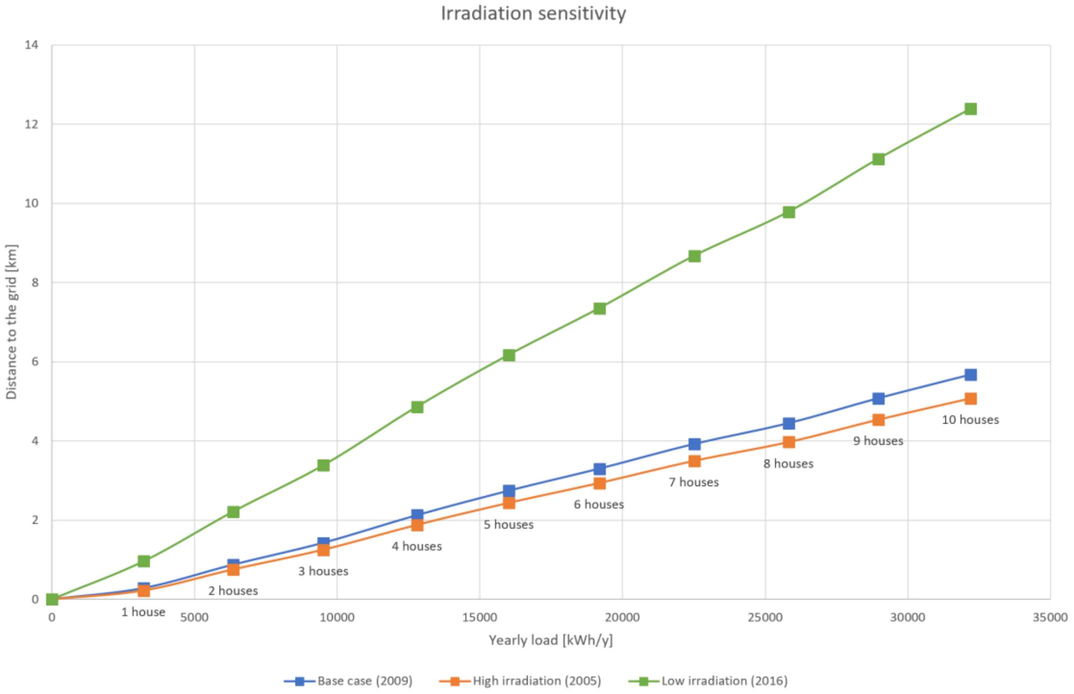


Figure 40 Threshold distances of the business case depending on the irradiation

Load uncertainty

The other uncertainty on the oversizing of the system is related to the load. On the base case, the yearly consumption per house was set to 3270 kWh [45], which is the value given by the TSO. However, it is known that the consumption behavior in rural areas is not exactly the same as in the rest of the country. For example, the cooking and heating systems commonly are not electric, leading to much lower yearly consumptions. Therefore, the load also represents an uncertainty that has to be checked.

Six extra simulations were performed for the one house system to see the price and asset size differences for each of the cases. The consumption values were changed to 4050 kWh/y and 4460 kWh/y for the cases with more consumption and 2480 kWh/y, 1880 kWh/y, and 1874 kWh/y for the cases with less consumption.

Figure 41 shows the PV installed in each of the cases explored. As expected, the PV installed increases with the yearly demand because more energy will be needed to supply the community.

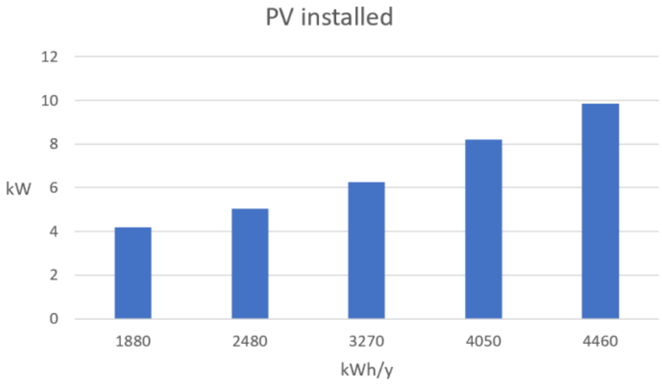


Figure 41 PV installed to cover the demand in each of the cases

Figure 42 shows the battery power and capacity for the different yearly loads. It can be seen that the battery remains more or less constant for cases with higher consumption. This is partly because the appliances present are the same, and little extra power is needed. For the energy capacity, it increases with the yearly demand, as with the PV.

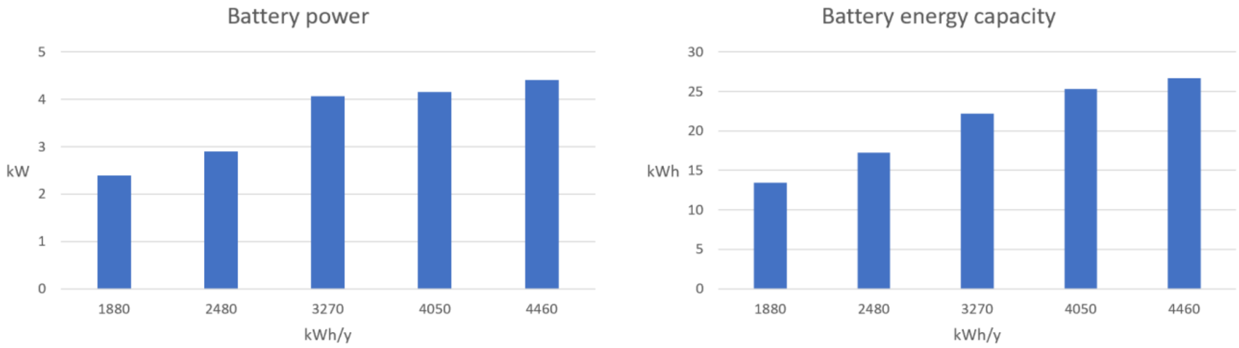


Figure 42 Battery power and energy capacity for each of the cases

Figure 43 shows the price of the assets of the microgrid for the 5 yearly loads considered. It can be noted that it follows the same trend of the PV and battery capacity because it depends directly on that. For the case with 4460 kWh/y, which supposes a 36% increase in load compared with the base case, a price increment of 29% is observed. On the other extreme, with an 1880 kWh/y, which supposes a decrease of 42%, a 39% decrease in price can be seen compared with the base case.

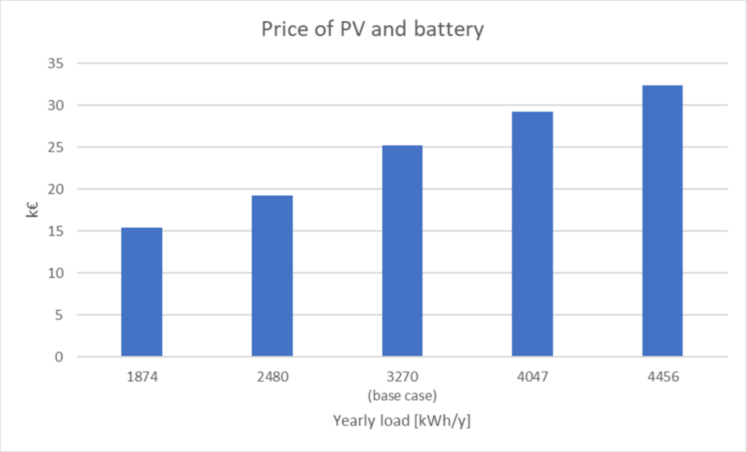


Figure 43 Price of the assets for each of the cases

Figure 44 shows the threshold distances as a function of the yearly consumption per household. For this case, as only the cases with one house were simulated, only the projections can be made, for bigger communities, by keeping the proportion of the distances in the 1-house case. However, this procedure may be inaccurate because, for 1-house communities, the microgrid price (15 k€-32k€) is very similar to the transformer price (17 k€), therefore giving very optimistic proportions. For the lowest consumption (-42%), an 83% decrease in the threshold distance can be seen compared to the base case. For the highest consumption (+36%), an increase of 61% is observed.

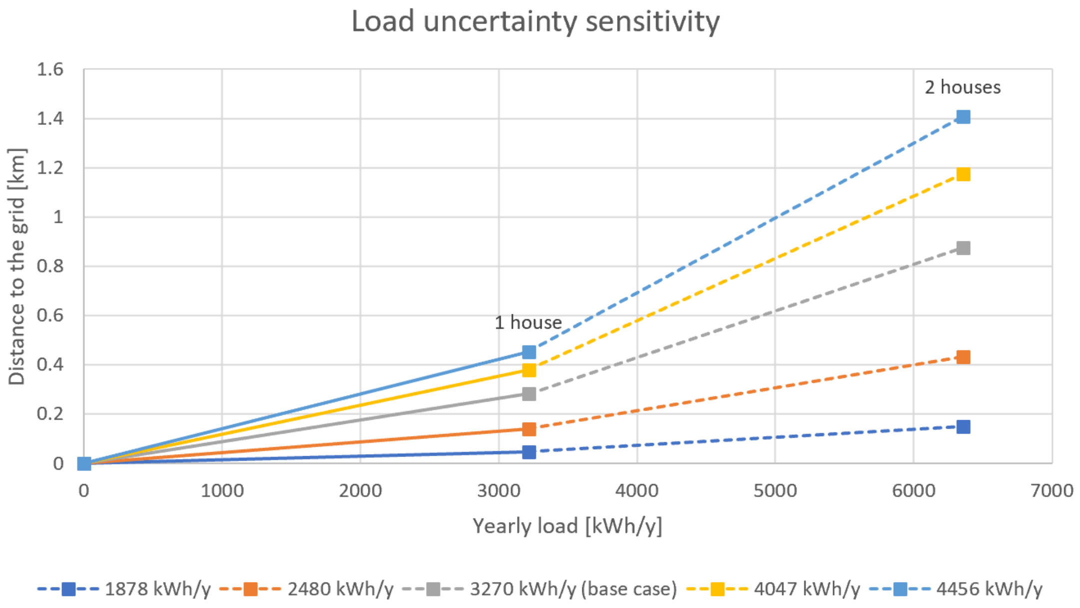


Figure 44 Threshold distance as a function of the yearly load consumption per household

Battery lifetime

Nowadays, one of the main concerns of investors when financing renewable projects is the storage's lifetime. This topic has been studied and researched by many institutions, like IRENA [41]. Even if the most common is to refer to the battery lifetime by the number of years it can be in operation, the lifetime is usually defined by the total number of cycles done.

For this specific application, around one cycle per day is expected. With this charge-discharge frequency, the expected lifetime, according to current projects carried by Laborelec, is ten years[2]. However, a sensitivity analysis has been done to see how the project's total costs and threshold distances would change if the Li-ion storage system's lifetime were 7.5 and 5 years. Figure 45 shows the results of the battery lifetime sensitivity analysis.

As expected, the shorter the asset's lifetime, the most expensive the microgrid business case is, and larger distances are required to build the microgrid. For the 5 years case, where the battery has to be bought eight times (instead of four in the base case), the threshold distance is 8 km. This is a 40% increase in the threshold distances of the base case. For the case where battery lifetime is 7.5 years, this value is reduced to 17%.

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[2] Information retrieved from a personal interview with a member of Laborelec [40]

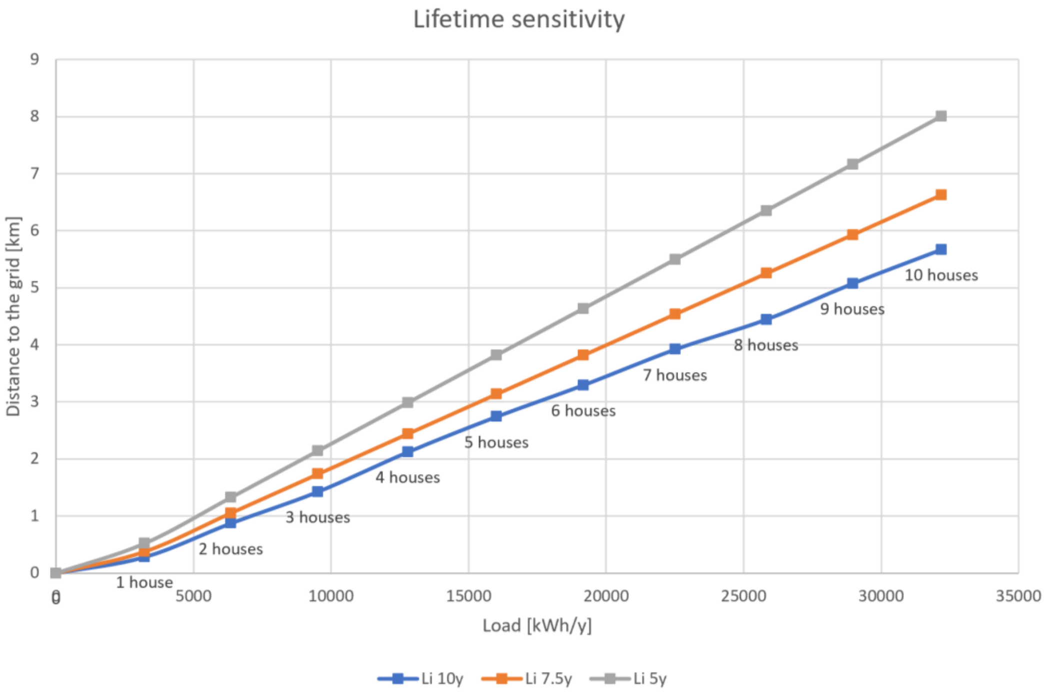

Figure 45 Battery lifetime sensitivity of the business case

Battery price and technology

Li-ion batteries' prices are usually dependent on the project's location, the type of battery, its size, and many others. That is why, even if Li-ion is a mature technology, there is still some uncertainty on the prices. For the base case, as can be seen in the methodology chapter, the prices for each kW and kWh installed were set to 300€ each, as recommended by Laborelec[3]. According to them, this is the usual price for very big projects, with several hundreds of kW of energy capacity. Therefore, the robustness of the solution was tested by increasing this price. In a medium price scenario, those were set to 400€, and in a high price scenario to 500€. In any case, Li-ion technologies' price is decreasing rapidly in the last years [41].

Moreover, as discussed in the methodology section, Vanadium Redox Flow batteries (VRF) were explored as well as a solution. Because of the E/P values for storage obtained in the simulations (8.5), a case operating with that technology was also considered. Usually, Li-ion batteries are used for projects with an E/P ratio between 0.25-4, while VRF is considered for cases with a ratio between 4-12. The prices of the technology were the most significant uncertainty. Several papers and documents were explored, but the technology's fast evolution pace made it very difficult to find consensus between the different sources.

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[3] Information retrieved from a personal interview with a member of Laborelec [40]

According to the European Association for Storage of Energy (EASE), the CAPEX price range for this kind of battery is 100-400 €/kWh and 500-1300 €/kW [61]. Similarly, Lazard made a study on the Levelized Costs of Storage (LCOS) [62], based on existing projects, and used as a range for the VRF batteries 271-819 $/kWh. In 2016, IRENA also studied the topic [63], setting the typical prices at 350-800 $/kWh and 1200-2000 $/kW. Laborelec, the R&D department of ENGIE Impact, recommended a power cost of 850 €/kW and an energy cost of 175 €/kWh, in the lower range of the values provided by EASE. However, none of these sources differentiated the price based on the battery's size and probably were giving values for big sized projects.

A research paper made by KIT scientists in 2016 was found [64], where price discrimination was given according to the size. The energy cost was always set to 400 €/kWh. The power price for small batteries (2kW) was set to 3000 €/kW, significantly more than the medium-sized (5 kW) set at 2000 €/kW. Finally, for batteries larger than 10 kW, a price of 1500 €/kW was assumed. Compared with the other sources, these values are very conservative. They are in the upper range of the prices given by EASE, and they double Laborelec prices.

Nevertheless, these values were selected to grasp the potential of Vanadium Technology. The small battery prices were used in the 1-house case and for the medium battery for the 2 and 3 house cases. For the rest of the cases, the large battery values were used.

As a reminder, the roundtrip efficiency of VRF batteries was set to 70%, lower than the 85% of Li-ion, and the depth of discharge was set to 100%. The battery lifetime was considered to be 20 years, following the most conservative estimations. Finally, the OPEX costs were considered 2% of the CAPEX, as in the Li-ion case. The prices considered can be seen in Table 10.

Table 10 Prices considered for sensitivity study of Li-ion and VRF batteries

Technology	Power Costs [€/kW]	Energy Costs [€/kWh]
Li-Ion Base Case	300	300
Li-Ion Medium Price	400	400
Li-Ion High Price	500	500
Vanadium Redox Flow	1500	400

Figure 46 shows the comparison of the threshold distances for different prices of the Li-ion battery, as well as for the VRF battery. It can be observed how the different prices on Li-ion batteries affect the business case. For the medium prices, which correspond to a 33% increase of the base case battery, it can be seen how the project's threshold distances increase nearly 24%. Furthermore, in the high price case, with an increase of 66% of base case's prices, the increase in the distances is slightly over 50%, with a threshold distance over 8 km for the ten houses community. This result is not surprising, considering that the storage accounts for more than 50% of the microgrid's total prices.

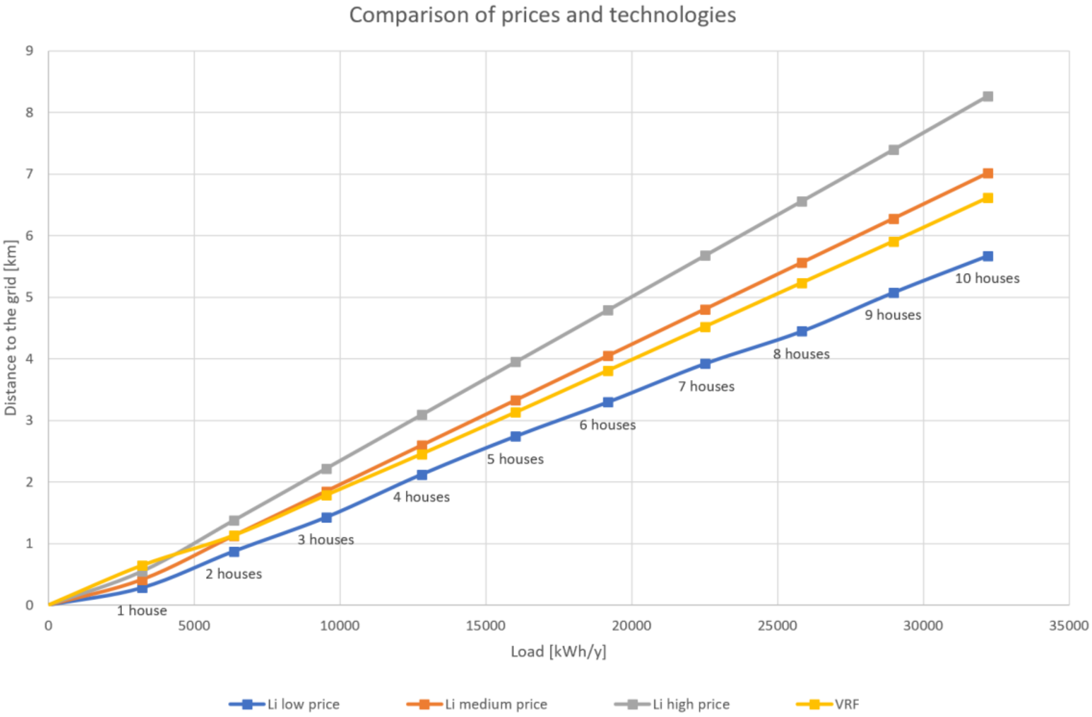

Figure 46 Comparison of Li-ion prices and VRF battery

Compared with the VRF battery case, it can be observed that, even if the most conservative prices were used to evaluate the technology, it is more competitive than the medium Li-ion prices for communities bigger than two houses. The main reason for this result is the long lifetime of this battery, which doubles the Li-ion one. This fact compensates for the high power costs of the technology. Therefore, if EASE's low range prices or Laborelec prices were used, which are half or even a quarter of the prices considered in the simulation, there is no doubt that VRF would be a more competitive technology than Li-ion for this business case. Moreover, the battery's rebalancing possibility discussed already in the previous chapter may push the costs down even more.

Preliminary studies were done using favorable prices for VRF, and reduction potential of 30% for the threshold distances compared with the base case for Li-ion was obtained.

These results show the high potential of VRF battery technology. However, Li-ion is much more mature, and it is easier to get financed by investors.

Diesel/ bio-Diesel

Commonly, isolated microgrid projects have an internal combustion engine, usually diesel, to generate back-up energy. The machine can supply power whenever the generation of renewables is not enough. By installing it, the oversizing of the system would not be needed at all. Moreover, probably *Prosumer* is oversizing all the assets itself in order to provide power to a few hours of the year when the renewable production is low. It is also a very cheap way of producing electricity.

However, installing a diesel engine also has downsides. The first one and the most evident is the pollution that it generates. In a world facing out from traditional fossil fuels, it would not be appealing to promote this kind of technology. Furthermore, diesel prices are not constant, but they fluctuate significantly over time, adding another uncertainty to the business case. Another obstacle for the installation of diesel engines is that they need a lot of maintenance, in addition to refueling periodically. If the microgrid is meant to be located in an isolated place, the idea of traveling there constantly should be avoided as much as possible.

For all these reasons, adding a diesel engine was not considered in the base case. However, simulations were performed to assess how big the advantage of adding it to the microgrid system would be.

The default parameters given by Laborelec were used for diesel engines. The cost was set to 400 €/kW, and the efficiency ranged from 34% in the case of supplying the minimum power to 40% when supplying at nominal power. The minimum power was set to a quarter part of the nominal one.

The main uncertainties to input in *Prosumer* for diesel are:

- Cost [€/kWh], which is variable. Extracted online from [65] (1.02 €/l); and divided by the energy density of diesel, 35.86 MJ/l, a value of 0.1023 €/kWh is obtained;
- Pollution [ton CO_2/kWh]. The value 0.000264 ton CO_2/kWh was extracted from [66];
- CO_2 market price [€/ton CO_2]. This variable was consulted in [67], and a value of 21.5 €/ton of CO_2 was used.

Simulations were done, including diesel engines, without any limitations in the usage or power installed. It was found that the case with the diesel engine reduced both the PV installed and the battery size to a third. This significant decrease was expected because previously, the system was oversized to ensure electricity supply for a few hours in the year when renewable generation is very low. Diesel engines can be used as a back-up generator. These diminutions in the asset's capacities implied a reduction of 50% of the project's total discounted costs, including the costs of the fuel, O&M, and CO_2 emissions.

However, it must be taken into account that the result obtained was optimized by minimizing the total discounted costs equation. In a real project, the CO_2 emissions should also be considered for minimization.

In light of the results obtained, it can be concluded that internal combustion engines have huge cost reduction potential for the business case. Other more environmentally friendly solutions, like biodiesel or hydrogen, could be used to substitute diesel engines while maintaining the benefits of having a combustion engine or fuel cell for a back-up power supply.

4.5 Discussion points

This section aims to discuss some controversial topics around microgrids.

At the end of the section, an approach to a real case will be performed to grasp the potential savings that this solution has.

4.5.1 Microgrid ownership and business model

This thesis's main goal has been to compare the microgrid business case with the MV line one. An economic comparison of both cases has been made. However, some legal and financial issues still have to be discussed.

There is no doubt that the MV line project would be paid by all consumers and managed by the distributor company because it is its responsibility to supply every customer with electricity. However, for the microgrids, the case is not that simple. Microgrid capital costs include generating assets, like PV panels, which cannot be owned by distribution companies due to the liberalization of the electricity generation activity [68].

After some research made on real projects, the following cases have been found regarding the ownership of microgrids [69] [70] [71]:

- Publicly owned: Through municipal or regional investment programs.
- Privately owned: Assets bought by a private entity, for example, utilities, third parties, or by the community benefiting of the microgrid itself.
- Public-private partnerships: Where agreements are made by public entities to help financing the project.

The owner of the assets also has the responsibility of operating and maintaining in good conditions the microgrid system.

Regarding the business models used to obtain revenues from the microgrid, the most common are [72] [73] [74]:

- Customer-owned business model: When the system is owned and controlled by the people who are its customers. This model places all the financial risk on customers. The main obstacle for this model is the high capital expense that should be paid.
- Microgrid-as-a-service (MaaS): It offers a flexible ownership structure. This is essentially a Power Purchase Agreement. This model reduces financial risk and enables more microgrids to become a reality. Moreover, partnerships can be done with entities that specialize in power systems and how to design, operate, and maintain them.
- Pay As You Go: Instead of regular, fixed payments (MaaS), customers pay for the service they use. They do not receive any service for which they have not first paid. Consequently, payments can be made in smaller amounts, which is beneficial in low-income areas. Customers also have greater control over their consumption. All the financial risk is on the owner.

4.5.2 Energy savings

The worst-case scenario and parameters were always chosen in the comparison made previously between building an MV line or a microgrid. This was done in order to be as conservative as possible with the microgrid business case. However, an important subject was not considered due to legal uncertainties but has an important role in determining the optimal result: who pays for the energy.

When building an MV line, the distributor is in charge of the project, with the supervision of the regulator of the country. At the end of the day, the project is paid with public funds, that is to say, by all the consumers. Any marketer can use the distribution line to supply electricity to the customers, paying the corresponding fee.

If a microgrid is built, the case is not so simple. The crucial difference lies in the fact that the electricity generating assets are being paid, unlike in the MV line case. Independent of the microgrid's financial model, it is evident that the generating assets are generating a value, electricity, which has to be considered somehow.

In this section, the discounted value of the generated electricity during the 40 years of the project is going to be estimated. This value is supposed to be subtracted from the total discounted microgrid costs, making the case cheaper.

For the calculation of the electricity value, the average prices of the energy and power of the regulated market in 2019 were taken [75]:

- 0.1042 €/kW per day

- 0.1527 €/kWh

The calculations were made with the assumption that this price is kept constant for the 40 years of the project. The yearly demand of the community is also considered constant during the lifetime of the project. No inflation was considered in the calculations. The discount rate considered was the same that was taken for the microgrid assets and MV lines, which was extracted from an IRENA report [29]: 7.5%.

$$NPV = C_0 + \frac{C_1}{1+WACC} + \frac{C_2}{(1+WACC)^2} + \cdots + \frac{C_{40}}{(1+WACC)^{40}} \qquad (7)$$

Using the NPV formula above, the discounted price per kW and kWh was found for the 40 years:

- For the power, it was found that the discounted costs are 519 €/kW
- For the energy, a price of 2.08 €/kWh of yearly load was obtained

Multiplying these two values by the power needs and yearly load of the community, the results in Table 11 are obtained.

Table 11 Discounted costs for the energy and the power of the community

Number of houses	1	2	3	4	5	6	7	8	9	10
Discounted price for energy and power 40y	8.8 k€	15.8 k€	23.3 k€	31.1 k€	38.9 k€	46.2 k€	53.7 k€	60.9 k€	67.8 k€	75.8 k€

This price should be included in the comparison because the electricity generated by the PV if the microgrid is built should have been taken (and paid) from the main grid otherwise. Therefore, these amounts can be considered as “energy savings” of the microgrid business case.

As a reference, these values represent on average 25% of the total discounted costs of the microgrid, obtained in the previous chapter. Consequently, a quarter part of the costs could be recovered from selling the electricity produced to the customers, making the microgrid case even more economically favorable.

4.5.3 AC vs. DC configurations

The microgrid’s electrical system cost and components will depend on whether it runs with AC-coupled or DC-coupled configuration.

Figure 47 [76] shows the simplified schemes of AC and DC microgrids. Depending on the specific circumstances, the optimal solution will change [77] [78].

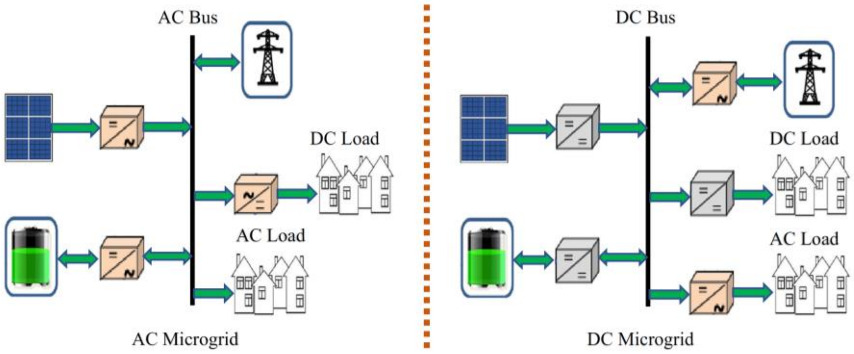

Figure 47 Simplified schemes of AC and DC microgrids.

Since batteries are charged with DC power and solar PV output is also DC, with the help of a DC-DC converter at the solar array's output, the battery could be charged avoiding unnecessary conversions to AC, implying losses and extra assets. Moreover, there is no reactive power and harmonics with a DC-coupled system, and there is no need to synchronize generation, leading to higher power quality. This approach has been proven as a cost-efficient solution by Gandini and Almeida [79], Karabiber et al. [80]. However, sometimes the low voltage levels lead to high currents, making more expensive some components like cables. Besides, all the households' loads usually are AC, which will require a central inverter to convert the DC power to AC. This kind of layout is challenging to expand in the future, and protective systems required are more complex due to the immaturity of its standards and guidelines and the lack of practical experience. The DC-coupled configuration also has lower reliability.

Consequently, the most modern off-grid systems use AC coupling, where all the loads can be connected to the same AC bus. This configuration makes that when the battery is charged from the PV, the process losses will be higher due to the two conversions needed (DC-AC-DC). However, considerable efficiency is obtained when supplying the power directly from the PV. This kind of layout provides higher reliability to the system, and it is easier to expand in the future [80].

Liu et al. [81] studied the reliability of microgrids depending on the topology, evaluating both AC and DC topologies. They concluded that the reliability depended mainly on the proportions of AC and DC loads of the system, obtaining fewer interruptions for DC topology whenever the DC load proportion was greater than 0.4. Also, the DC components are less reliable than the AC ones.

In recent years, a new kind of architecture has been studied and developed, the hybrid one. This architecture is meant to have the advantages of the other two types. It uses an AC bus to supply the AC load and a DC bus to supply the DC loads. Also, the generation sources are connected directly to the AC or DC bus, depending on which option minimizes the conversion steps and the losses.

4.5.4 Locations with potential

In this section, the areas with more potential will be characterized, and a real case will be explored.

Two parameters can serve us as guidelines to find areas with optimal conditions to build microgrids. These are population density and population dispersion.

Regions with low population density have very long distribution lines built to supply small population groups. Therefore, those areas' distribution systems have a very high cost per customer supplied.

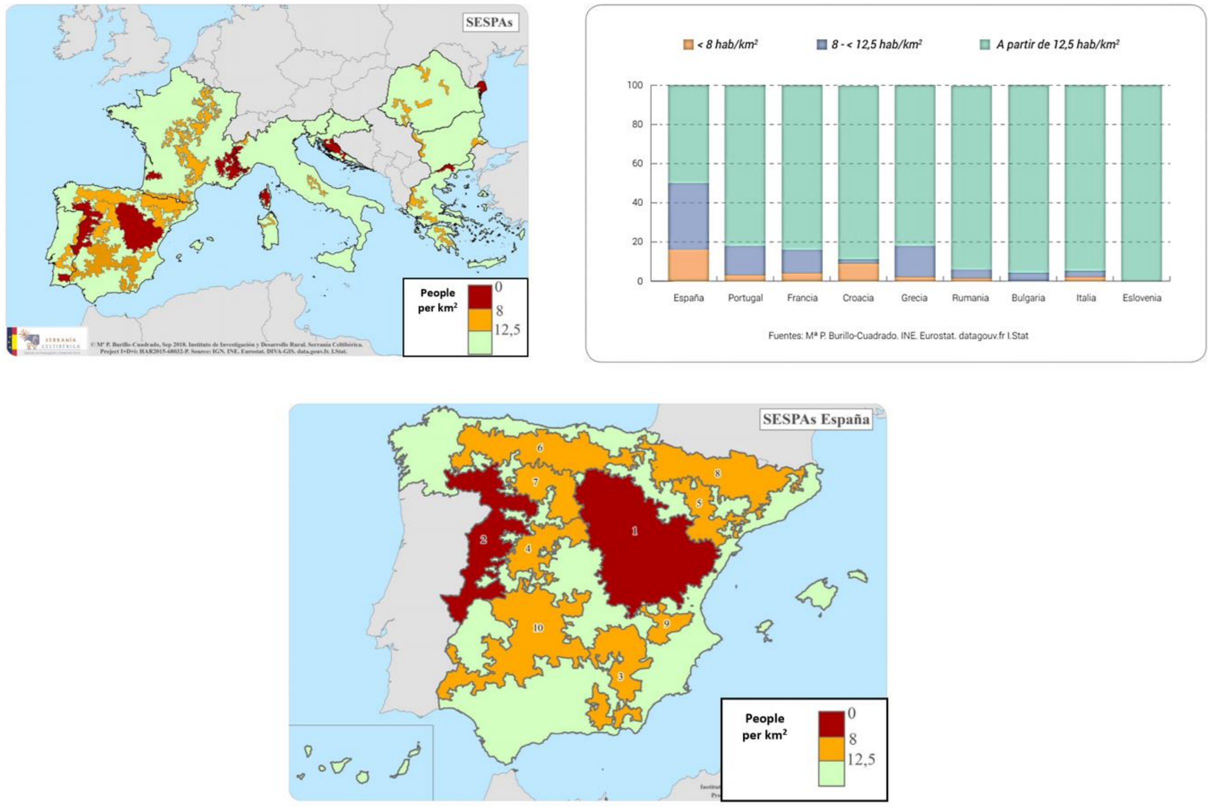

Figure 48 Population density of southern Europe and Spain

By far, Spain is the southern European country with a more significant part of its territory sparsely populated. Figure 48 [82] shows the population density of southern Europe countries, together with the percentage of territory sparsely populated. It can be seen that around 50% of Spanish territory has less than 12.5 inhabitants per km^2, compared to less than 20% for the second country on the list. Furthermore, 53% of the Spanish territory is occupied by only 5 % of the population.

In the north-east of Spain, there's a territory called *Serranía Celtibérica*, also known as the Lapland of the south, because its low population density is only comparable with this region in Finland, that can be seen in red in Figure 48. It is considered a demographic desert, with an average of 7 habitants/km^2 [83]. However, some significant areas inside this territory can reach a density as low as 4 people/km^2. This is the case for Guadalajara.

Thus, in all the territories highlighted on the map, which have an extremely low population, microgrids can be an excellent option to consider as a replacement of the aged MV lines.

In Spanish rural areas, three different kinds of settlements can be distinguished.

Figure 49 [82] shows the types of settlement and the dispersion index on the Spanish territory.

- The concentrated, more typical in the center and south of the country, where all the houses are built close to each other. Usually, they are located in plains where water resources are scarce.
- The disseminated or dispersed, more typical in the north, where the houses are built at a considerable distance one from the other. Usually, they are located in mountainous territories, where water and natural resources are abundant
- The mixed one, which is a mixture of the two previous.

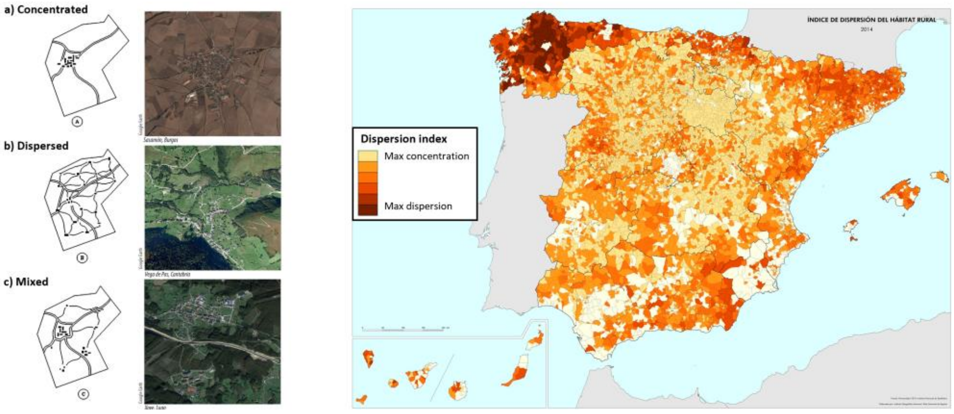

Figure 49 Types of settlements (left) and dispersion map of Spanish territory

The population dispersion is also an interesting parameter to consider when exploring regions with potential for microgrids because a highly dispersed area will lead to longer distribution lines to supply all the customers, increasing the system's costs.

Real case

The solution's potential may be difficult to grasp from this thesis's results because most people do not know the typical distances from the main grid to the villages. Therefore, a real case of a Spanish village is shown in this section to clarify microgrids' potential and calculate the expected savings.

The village selected for the case was Ocentejo, in the province of Guadalajara. This village is located inside the demographic desert mentioned in the previous paragraphs.

Ocentejo population evolution is very representative of the demographic problems present in this area. Figure 50 shows the population evolution of this village since the year 1900. According to the National Statistics Institute [84], at the beginning of the 20th century, Ocentejo had a population over 250.

However, since the second half of the 20th century, this number has decreased dramatically due to the migration to urban areas. Nowadays, 18 people are still living there.

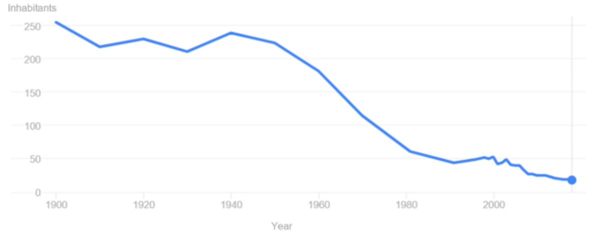

Figure 50 Population evolution of Ocentejo

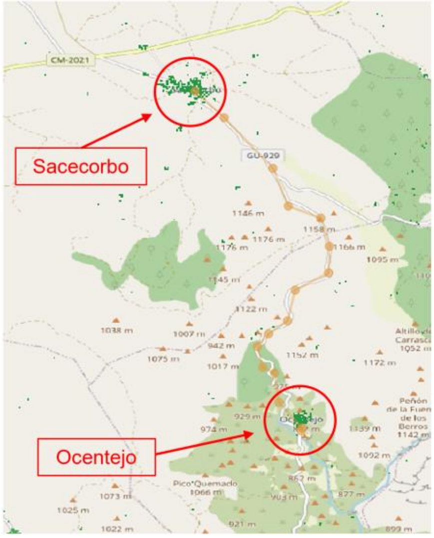

Figure 51 Map showing the distance between Ocentejo and Sacecorbo

The village is surrounded by mountains, and it is only reachable through a small curvy road. Figure 51 shows the location of Ocentejo and Sacecorbo (the closest village) on the map. The closest village in the surroundings is Sacecorbo, with 85 inhabitants. The distance between both villages by car is 9.3 km, which can be considered the MV line's distance.

Looking at the base case results obtained in the previous chapter, it can be seen that for an 18 people community (around six houses in terms of energy used per year), the threshold distance is 3.3 km. For distances greater than that, it is economically better to build a microgrid. In this case, the real distance is almost three times the threshold distance. Thus, this would be a perfect location to build a microgrid.

In the previous chapter, the estimated price for six houses microgrid was obtained: 191730 €.

If the equation to compute the costs of the MV line is used, setting 9.3 km as the distance to the main grid, the total costs of the distribution line can be obtained: 509640€

Therefore, there is a significant difference between the costs of both projects. If the two values are subtracted, a saving potential of 317910 € is obtained.

In addition to economic reasons, social reasons play in favor of the microgrid case. The population evolution trend is not expected to change in rural areas. If the most pessimistic predictions are considered, hundreds of villages will be uninhabited in the next decades. Around 4200 municipalities in Spain have a severe lack of population, and 1840 are at risk of extinction [85]. Moreover, 45% of the people of those villages are over 65 years old. Thus, building an MV line to those places would be a waste of money and resources. On the other hand, the main microgrid assets, like PV and batteries, can be easily reused in other projects around the country if a village happens to be completely deserted.

5. Conclusions

In this master thesis, the feasibility of installing an isolated renewable-based microgrid has been compared against the construction of an MV line for remote rural communities in Spain. More specifically, all the microgrid's energy was produced from PV modules, which provided electricity to the customers with the help of a battery.

In order to do that, a load forecast model for individual dwellings was developed. It allowed the pseudorandom simulation of small rural communities' yearly demand profiles, with a high degree of customization. The model could be successfully adapted to Spanish rural areas' behavior, giving precious input for the simulations that could not have been obtained otherwise. This model can be used in the future to simulate small communities whose appliance configuration and behaviors are known. It can be useful for asset sizing optimization, as it has been proven in this thesis and many other topics, like demand response studies or grid stability studies, among others. It can help overcome the lack of available information on the internet related to individual dwellings' load profiles.

Afterward, the yearly demand was used together with other economic and technical inputs to optimize the PV modules' capacity and the battery. This optimization was done with *Prosumer*, an advanced simulation and optimization tool developed by Tractebel Advisory & Advanced Analytic. The final results showed that the optimal configuration for a 1-house system (equivalent to 3 people living) was a 6 kW solar PV installation combined with a 4 kW and 22 kWh battery. These values increased linearly with the number of houses. The 10-house system (30 people) optimal configuration was a 59 kW PV installation and a 30 kW and 237 kWh battery.

Therefore, the approximate increase rate for each extra house included in the simulation was +6 kW/house for solar PV, together with +3 kW/house and +25 kWh/house for the battery. This result is valuable because the loads for each extra house were generated independently one from the other. Yet, the trend followed by the size of the assets is consistently linear. Therefore, the result can be easily extrapolated to bigger communities.

However, more costs had to be considered to have a realistic cost estimation. These costs included the soft costs, the control system's cost, the cost of electrical equipment, and land cost. All these were estimated based on existing microgrid projects. This allowed computing the microgrid's total discounted cost for the 40 years duration of the project. A value of 32 k€ was obtained for the 1-house system, which increased to almost 320 k€ for the 10-houses community, following a linear trend like the assets. The rate of increase of the costs was +32 k€/house. In other words, the total discounted cost is 3.6 million €/MW, a value that is in line with other similar microgrid projects registered in the US.

Once the total discounted costs were obtained for the microgrid business case, the same had to be done for the MV lines. For this purpose, a very insightful, legally binding document describing the regulated costs for all the distribution assets in great detail was found. With this data, the MV lines' discounted prices for a 40 years project were obtained, leaving the distance as a variable. For the lowest of the voltages considered (1 kV-12 kV), a total discounted price near 53 k€/km was obtained for the 40 years. This price increased for higher voltages, reaching around 76 k€/km for the highest voltages considered (24 kV-36kV). The MV/LV transformer also was considered, with a total discounted cost of 17 k€.

The total discounted costs of both cases were equalized to compare the microgrid with the MV line. As a result, a formula for the threshold distance from which the microgrid business case is more favorable was derived. For one house (or three people), it was found that it was better to build a microgrid for distances greater than 280 m from the main grid. The threshold distance increased linearly with the number of houses in the system. For the ten houses case, that distance was found to be 5.6 km. Averaging the results for the ten different communities simulated, it can be concluded that the maximum MV line length that can be built per customer is 187 m. If the length per customer is greater than that, a microgrid should be considered instead, from an economic perspective.

Some sensitivity analyses were done afterward to assess the robustness of the solution under the main uncertainties.

The cheaper and simpler MV line was considered for the base case; therefore, a sensitivity analysis was done considering other more expensive MV lines (with greater voltages). In the most expensive case, the threshold distances were reduced up to 30%, making the microgrid case positive for a greater number of cases.

An oversizing sensitivity was performed to ensure the energy supply during all the year. It was seen that this parameter affected a lot the business case, increasing the threshold distances considerably. For a 50% oversizing, an increase of the threshold distances of slightly more than 50% was observed. Therefore, a very accurate calculation of the project's safety energy margin must be performed to avoid over costs.

The oversizing needs to be done for two reasons, weather and load uncertainties. In this context, sensitivity to the weather conditions was performed. Two years, with exceptionally high and low irradiation values, were selected to perform new simulations. It was seen that for the year with high irradiation values (6.7% more than in the base case), *Prosumer* added more PV and reduced the battery power and energy capacity. As a result, the price of the microgrid was reduced by 10%. On the other hand, for the case with a low irradiation value (7.2% less than in the base case), *Prosumer* increased the PV installed as well as the battery’s power and energy capacity, leading to a huge price increase of 112%.

For the high irradiation case, the business case's threshold distances decreased by 12%, and for the low irradiation case, they increased by 119%. These results indicate the negative exponential nature of the costs as a function of the irradiation. In conclusion, it is important to have very stable weather conditions in the location of the installation. A solution to this problem could be an internal combustion engine.

The other sensitivity related to oversizing was load uncertainty. Four extra simulations were done for the base case with one house, two with a higher yearly load, and two with a lower yearly load. With a 36% increase compared to the base case, the simulation with the highest yearly load experienced a price increase of 29%, mainly due to the extra PV and battery energy capacity installed. For the case with the lowest load, with a decrease of 42% compared to the base case, a 39% decrease in price was observed.

Another of the uncertainties for most of the investors in this kind of project is the battery lifetime. Sensitivity analyses were performed for batteries in which life was half (5 years) and three-quarters (7.5 years) of the expected lifetime. The threshold distances were found to increase by 40% and 17%, respectively. These values are expected because the storage is the most expensive microgrid component, representing more than half of the total costs. If the lifetime is substantially reduced, more batteries will have to be bought during the 40 years project.

The price of the Li-ion batteries was also included in the sensitivity analyses. The price set in the base case was 300 €/kW and 300 €/kWh, which is an optimistic price, usually seen in big scale projects, over 1 MW. However, as the size considered in this study is much smaller, it would not be surprising to find more expensive batteries. If a 66% increase in the storage system's price was considered (500€ per kW and kWh), a 50% increase in the threshold distances was observed. As in the previous sensitivity, big changes are expected due to the high proportion of the storage costs compared to the total.

Due to the high energy to power ratio obtained in the optimization of the assets, the Vanadium Redox Flow battery was considered as a technology for the storage in substitution of Li-ion batteries. Despite being significantly more expensive than Li-ion batteries, the longer lifetime of this kind of battery (20 years) made it very competitive. With very conservative cost values, this technology's threshold distances were very close to the base case. Some preliminary studies were done with optimistic costs, and reduction potential of 30% on the threshold distances could be seen compared to the base case. Moreover, the electrolyte's rebalancing could be done on this type of battery, reducing, even more, the price of replacing the battery. In conclusion, even if this technology is still not as mature as Li-ion, it holds huge potential as the storage technology of renewable-based isolated microgrids due to the high energy to power ratio they have and the considerably long lifetime.

As a last sensitivity, a diesel internal combustion engine was included in the generation mix. It was observed how, with the inclusion of this back-up energy generator, the PV and battery capacities were reduced to a third of their original size, leading to a reduction in total discounted costs of 50%. This reduction was due to the oversizing that the software has to do to supply the electricity in those times of the year when the solar irradiation is exceptionally low. Even if the results were obtained without a limitation on the CO_2 emissions, it could be seen how the addition of an internal combustion engine to supply in those hours with low renewable generation can be economically very beneficial. Therefore, to stay loyal to the renewable-based microgrid, other alternatives to diesel, like biodiesel or hydrogen, could be considered to do the same task.

As the last consideration of the comparison between microgrids and MV lines, the microgrid case's energy savings were computed. These energy savings represent the value of the energy produced inside the microgrid that otherwise would have been taken from the grid. In the microgrid business case, the generating assets are being paid. In contrast, in the MV line case, only the assets responsible for transmitting the electricity are being taken into account. On average, these energy savings represented 25% of the microgrid's total discounted costs, which is a significant amount. This result makes the microgrid business case more favorable than before, reducing even more the threshold distances.

To finish the thesis, a preliminary analysis of the savings on a real case was computed. The areas with the most potential were identified and explored. Several villages were easily found with an optimal location and size during the research to implement a microgrid. As an example, the village of Ocentejo was identified, and the potential savings were computed. Those savings were found to be well over 300 k€, representing the huge saving potential of renewable-based microgrids as substitutes of aged MV lines in Spain.

As a final conclusion, microgrids' feasibility to substitute MV lines in Spain has been checked, and the necessary conditions to make the business case favorable have been successfully identified. Even if the simulations' values were conservative, the business case proved to have a huge potential.

Future work on the topic should be directed towards the cost reduction of the microgrid by exploring other storage technologies and the inclusion of an internal combustion engine as a back-up generator. Once the threshold distances are known, estimating the potential number of cases where the solution could be applied in southern Europe should also be researched.

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