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Sizing of renewable energy production and storage solutions for increasing the energy autonomy of tertiary buildings

Thesis presented in order to obtain the Master's degree in Civil Engineer in Data Science

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Abstract

The access to electricity as renewable as possible is increasingly in demand. Sometimes, the connection to the public is either impossible or not wanted. Therefore, the local network must equip itself with electrical production and storage solutions. This master's thesis aims to develop and implement an algorithm for sizing production and storage solutions for the electricity supply of tertiary buildings while minimizing the use of fossil energy sources. Three versions of a model were formulated: one considering a long-term investment project with variation in the demand over the year, one restricting itself to yearly data, and a final one modeling the annual demand thanks to representative days. Two objective functions have been defined and used in these three models: the maximization of the installation's Net Present Value with a penalization on the use of fuel and the minimization of the CO_2 emissions linked to the project. The different combinations of these three models and two objective functions have been applied to five cases with various consumption profiles. The model with a one-year horizon with a minimization of the CO_2 emissions performs best. Further developments and improvements as the integration of additional production and storage solutions or the consideration of the electric vehicles' consumption and batteries worth to be explored.

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Chapter 1

Introduction

1.1 Context

In this world of ours, with continual technological advances and growing needs, energy is one of the key resources. Humans need energy to light up, produce food, travel, work, entertain, ... In the context of climate change and global warming, it is critical that this energy is as carbon-free as possible. Some renewable energy production solutions have existed for years but are not sufficient yet to completely replace fuel-based energies. However, their technology constantly improves, and combined with willingness, investments, change in behavior and consumption, every human being can do their part of the hummingbird [1] to reduce their carbon footprint.

There is an increasing willingness to move towards more sustainable energy/electricity production methods: more and more roofs are covered with solar panels, wind turbines appear, hydroelectric power stations are installed, etc. However, these production methods are inherently variable and dependent on the weather. Even with batteries, if there is no sun and wind, a building cannot be powered up with renewable electricity. This is why almost every house, building, and shop is connected to the electricity network. Nevertheless, there exist zones in the world with no electricity network or places where people choose not to be connected; they are "off-grid". Therefore, there is a need for backup solutions for energy production if renewable ones are not sufficient such as (bio)gas, fuel, or hydrogen.

1.2 Objectives

Broptimize Energy S.A. (Broptimize) [2] is a Belgian company specializing in energy optimization. For their clients who would decide to be off-grid, the purpose of this project will be to create a sizing algorithm that optimizes the production and storage solutions in the case of an isolated building to minimize the carbon footprint of the installation.

Resources are limited; thus, there is a significant interest in optimizing their allocation. Although the goal is to isolate a building from the grid and power it up with renewable energy, it would be counter-productive from a general point of view to significantly oversize the green production and storage solutions.

There is a certain number of constraints to respect in a sizing algorithm for the model to be realistic. The most important constraint of the algorithm is to satisfy the demand at every moment of every day of the year. As mentioned, renewable energy production solutions are inherently variable, particularly solar panels and wind turbines. A set of batteries can partially respond to this variability by allowing the storage of some electricity to make it available for later. However, it might not be sufficient. Therefore, the energy solutions taken into account in the algorithm are:

- Wind turbines;
- Solar panels;
- Cogeneration plants, for the coupled production of heat and electricity;
- Diesel generator.

These solutions are just a carefully selected subset of a bigger ensemble of energy solutions. For example, hydrogen could also be a production and storage solution, as it was done in the article [3]. The hydrogen would be produced when the electrical production is higher than the consumption, stored, and used when needed. However, the current efficiency was not convincing, so this report will not investigate this solution. A connection to the electricity network is also a theoretical possibility if the off-grid situation is a choice and not imposed, given the location. Nevertheless, since a connection goes against being off-grid, importing electricity from the network would have to be penalized in the objective function. So, the electricity from the grid would probably be more or less equivalent to the electricity from the cogeneration plants and the diesel generator. In case it would not be penalized, the project's total costs would likely be significantly impacted, and the risk of oversizing would be reduced.

As mentioned, finding an objective function that tries to minimize the project's carbon footprint while not oversizing the production and storage solutions is important. The algorithm is tested with two objective functions to see their impact on the optimal solution. The first one is to maximize the Net Present Value (NPV), which is defined similarly as Selmane Dakir did in his article [4]. Maximizing the Net Present Value makes the project's financial value as high as possible, but fossil energy sources are penalized here to meet the carbon objectives. The second one is to minimize the CO_2 emissions of the project by analyzing each solution with its carbon equivalence.

These two objective functions could be linked by converting the CO_2 emissions into Euro. The question is: "What is the price to associate with a ton of CO_2 emissions?" As stated in the article [5], to align with the temperature targets set out in the Paris Agreement, the price for one ton of CO_2 in 2020 should be between 40 and 80$ and between 50 and 100$ in 2030. In 2023, these prices are higher than those of the CO_2 market in the world, except in Europe [6]. Nevertheless, depending on the client's climatic ambitions, this price could be tailored to each project.

The additional objective function would be max $NPV - CO_2 * \text{Price of CO2}$. However, the optimal solution might not be very different from those obtained with the other two objective functions. Actually, with different intensities, NPV and CO_2 both penalize the oversizing and CO_2 emissions. For the Net Present Value, oversizing has a significant financial cost, which should be minimized, and the fossil energy sources are financially penalized. For CO_2, the fossil energy sources have a high level of CO_2 emissions, which are minimized, and oversizing also has a cost in terms of CO_2 emissions (for example, more battery capacity means more resources used and thus, more CO_2 emissions).

1.3 Methodology

To carry out the design of the algorithm, a coherent model had to be built in line with Broptimize's wish and compatible with the available data. After a few meetings to clearly lay the foundations of the project, Broptimize shared some consumption profiles[1]. Five profiles have been selected for their diversity and are described later. With those, it was possible to test the optimization model and make it more complex step by step.

Nevertheless, a model can never represent reality perfectly; some physical and financial constraints have been neglected. But one must remember that the model is based on some electric production and demand estimations. The goal is to have a good sizing of the production and storage solutions, not to predict how the system will behave at every time step.

Eventually, three models are designed:

- The complete model: The complete model considers the whole lifetime of the installation. Since this represents significant investments and given the service life of wind turbines and solar panels, the lifetime will generally be around 15 years. Although this model is bigger and requires more computation resources, it can take into account future modifications, for example, in electricity demand. If the client anticipates an increase in its electrical needs because of the installation of additional machines, the hiring of several workers, or a switch of its car fleet towards electric vehicles, the complete model can represent it. In the same way, if the building is to be insulated or less air-conditioned, the complete model can represent a decrease in electrical demand over the years. In addition, reinvestments can be implemented in a several-year model. For example, new solar panels, with better efficiency, could be installed 5 years after the others if the demand increases and to compensate for the small loss in productivity of those already installed.

- The model on one year: This model only represents and optimizes over one year of demand, production, and constraints. For this model to be meaningful, the cost of the installations must be adapted; otherwise, high-investment solutions would tend to be disregarded. This model has the advantage of running faster and, thus, testing more (combinations of) parameters but all the potential variations of the demand and the reinvestments are disregarded.

- The model with representative days: In many businesses, some days are very similar to others regarding electric consumption. Therefore, this model focuses only on a set of representative days to optimize the sizing. The computation time will be reduced, but it is possible that the simplicity of the model will negatively impact the results. Their reliability and difference from the results of the other models are then studied.

After the design of the models, they had to be implemented. The programming language chosen is Julia [7], particularly for its packages JuMP and Gurobi. The solver used is Gurobi Optimization [8] with an academic license. Then, research was done to find coherent values for the numerous parameters of the model, which is detailed later.

Finally, the algorithm (the three models) was tested on the five profiles provided

[1]Broptimize only monitors the electrical consumption and not the heat consumption

by Broptimize. The results cannot have been empirically verified because it would have required installing and monitoring the suggested optimal solutions for years. However, the relevance of the results can still be assessed with a critical mind by people working in the field.

1.4 Outline

The second chapter of this report will review some of the literature linked to the topic of this master's thesis and discuss some theoretical concepts. Chapter 3 will gather information about the data used, the preprocess needed, and the characteristics of the different electrical production solutions. The preprocess will detail how the expected production data of solar panels and wind turbines are obtained. There is also a description of the five cases considered for the algorithm testing, with the level and structure of their electricity demand.

Then, Chapter 4 contains the formulation of the general optimization problem and the adaptations made for the two simpler models. It provides explanations of the meaning of the decision variables, the parameters and their values, and the constraints. The fifth chapter gathers all the results of applying the algorithm to the five cases and an analysis of them. Finally, the last chapter will conclude by summarising this report's interesting points, results, and recommendations.

Chapter 2

Theoretical background & Literature review

This chapter aims to give a general theoretical overview of three concepts used in this master's thesis: microgrids and mixed-integer programming to size them, carbon footprint, and the selection of representative days of a set of time series.

2.1 Microgrids & Mixed-integer programming for microgrid sizing

A microgrid is a small-scale electricity network, in most cases connected to the public power grid. The goal is to supply electricity to a group of users thanks to local production. [9] Although it is connected to a larger grid, a microgrid can "disconnect" itself from it in case of a power outage, for example, and operate in an "islanded" mode. [10] [11].

According to [9], to work, a microgrid must be made up of:

- A local installation of electricity production to ensure its autonomy if disconnected from the public power grid. The solutions are multiple to produce electricity locally and can be combined: solar panels, wind turbines, hydroelectric turbines, cogeneration plants, heat pumps, and biomass power plants. In addition, a backup production system (generator) must be installed.
- A storage system to stock electricity when the production exceeds the consumption and supply electricity when the combined production is insufficient. The possibilities are diverse, but mainly batteries, water reserve for pumped storage, hydrogen reserve, and in the near future, electric vehicle batteries [12].
- An intelligent management system to ensure a constant balance between electricity production and demand. The management system gathers a lot of data from the microgrid so that it is able to manage itself and make decisions.

Microgrids can pursue various objectives such as reducing the environmental impact of electric supply, ensuring diversity of energy supply, powering up a remote site, or increasing the reliability of power supply. [11]

Microgrids are interesting in various cases. Not every place in the world has access to a (reliable) power grid. For places that cannot be connected to a public power grid because of economic or geographical reasons, microgrids always operate in isolated mode. The purpose of the algorithm designed in this master's thesis is to size the production and storage solutions for this type of situation. In some cases, there is a willingness to be independent of public networks, such as during military operations, to improve physical and IT security. [9]

To properly design the algorithm, the concept of mathematical programming is used. It is defined as: "Mathematical programming is the mathematical study of problems which ask for optimal (minimal or maximal) values of an objective function on a given domain. This includes the study on existence of solutions, structural properties, as well as algorithmic aspects. [...] In general terms, mathematical programming models include a set of (1) decision variables, (2) an objective function, to be maximized or minimized by changing the level of the decision variables, and (3) a set of constraints that limit the domain over which the optimum is taken." [13]

Prof. Quentin Louveaux covers mathematical programming, including linear programming and mixed-integer programming (some variables must take integer values), in several courses he teaches at the University of Liège. The modeling techniques covered help to formulate the problems linked to the sizing of production and storage solutions in the case of an isolated microgrid. Arthur Richards and Jonathan How's article [14] explains how mixed-integer programming can help model many types of problems and the techniques used to solve them (also used by the solver Gurobi which is the tool used in this master's thesis to obtain the results presented in Chapter 5).

2.2 Carbon footprint

In the context of climate change and global warming our world is in, it is very interesting to know the carbon footprint of everyday objects: clothes, soap, meat, vegetables, cars, smartphones, solar panels, etc. Energy is needed to test, produce, transport, and recycle these objects. The carbon footprint of an object determines its environmental impact. To do it, one has to measure the greenhouse gas emissions (not only the CO_2 emissions) linked to all stages in the object's life cycle. "In general, to compute the carbon footprint of a product, are considered all the emissions of greenhouse gases caused by:

- The extraction of raw materials;
- The transformation of raw materials;
- Its packaging;
- Its modes of transport;
- Its consumption during use;
- Its end of life (how it is recycled or degraded)".[15]

Calculating the carbon footprint of everything around us has many benefits, including making better, or at least more conscious, consumption choices. With carbon footprints, different solutions can be compared with respect to their environmental impact, not only to their price. This concept of carbon footprint will be used in this master's thesis to compare the amount of greenhouse gas emissions linked to the different electric production and storage solutions the algorithm has at its disposal.

2.3 Selection of representative days

The design and sizing of microgrids require high computational resources because of the large amounts of data to deal with and the numerous simulations to run. To help reduce the amount of data, it is possible to select some representative days from the list of analyzed days and assign them a weight that indicates the number of days (out of the 365 of a year in general) they represent.

There are several methods to select representative days. Edwin Pinto's article [16] presents other methods for selecting representative days, such as Averaging, k-Medoids, and OPT, and evaluates them. Kelsey Fahi's article in the *Journal of Renewable and Sustainable Energy* [17] presents the Monthly Peak Preservation Method to select representative days which preserve demand peaks in the original profiles. Monthly Peak Preservation Method "reduces annual hourly demand data to 36 representative 24-h demand profiles, using one peak profile per month to preserve peak demand, and two profiles per month to capture average weekday and weekend demand." [17]

The method used for this project is the one set up by Sébastien Mathieu, available in his GitHub [18]. His code allows the user to extract a given number of representative days of a set of time series. Therefore, it is more flexible than the Monthly Peak Preservation Method because less than 36 representative days can be selected. In his article [19], Selmane Dakir shows that results with a high degree of reliability can be obtained with only 10 representative days.

To build the model with representative days, 12 days will be selected for each of the five cases considered. It is above the threshold of 10 days and, with 12 days, one day per month will be selected, on average. The main question left for the analyses made in Chapter 5 is: "How much is the quality of the results impacted while considering only 12 representative days of a year instead of the 365 days?".

Chapter 3

Data: Origin & Preparation

In this chapter, the reader can find a description of the datasets used for this master's thesis, the characteristics of the production solutions considered, and the main preprocessing steps.

3.1 PVGIS, an application to obtain data for estimating wind turbine and solar panel production

As mentioned, the two major production solutions proposed are wind turbines and solar panels. For this to be usable by the sizing algorithm, one has to provide it with an expected hourly electric production for each case. The Photovoltaic Geographical Information System (PVGIS) [20] was used for that. As stated in [20], "PVGIS is a web application that allows the user to get data on solar radiation and photovoltaic (PV) system energy production, at any place in most parts of the world. It is completely free to use, with no restrictions on what the results can be used for, and with no registration necessary."

PVGIS is an official website of the European Union. By indicating the geolocation of the place of interest, one can download the typical meteorological year information, including wind data, as shown in Figure 3.1, or indicate the solar panel installation parameters and obtain the hourly radiation data, as shown in Figure 3.2.

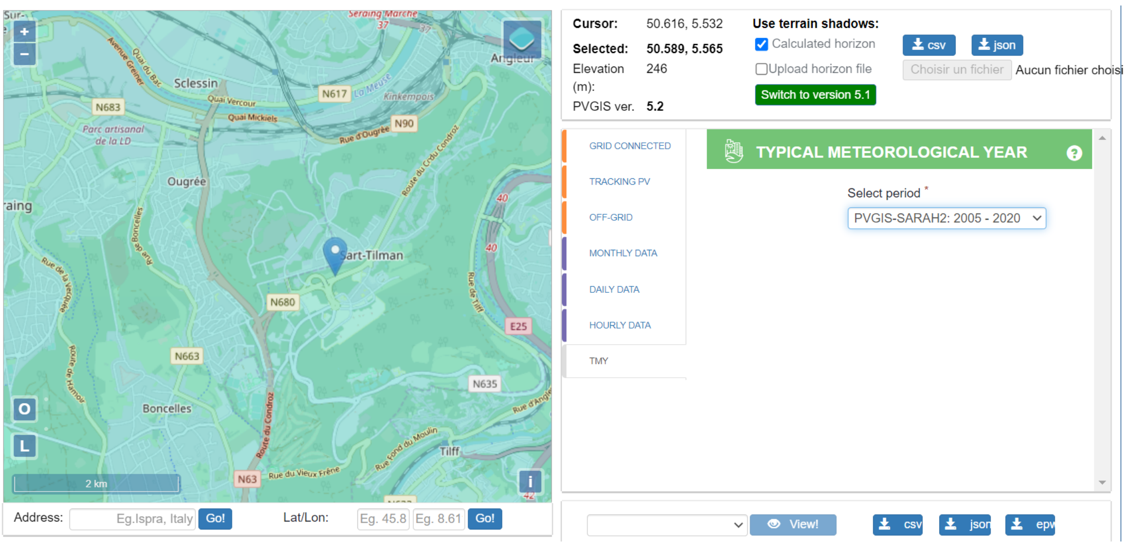

Figure 3.1: PVGIS interface for the procurement of the typical meteorological year data, including wind data [20] (to estimate wind turbine production)

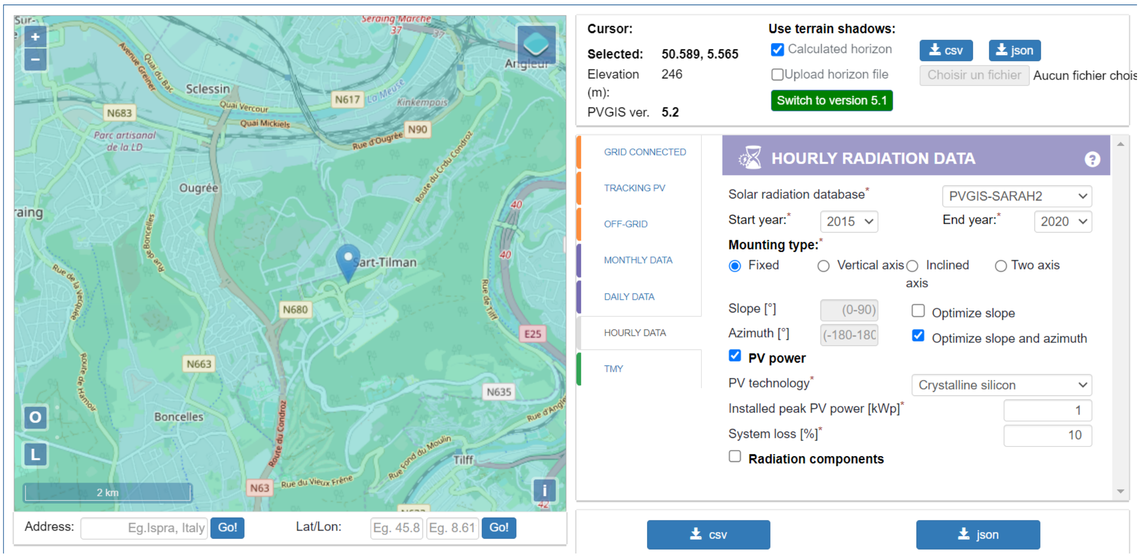

Figure 3.2: PVGIS interface for the procurement of the hourly radiation data [20] (to estimate solar panel production)

3.1.1 Estimating wind turbine production

Regarding the typical meteorological year data, the dataset furnishes information over several elements, more precisely: "the data set contains hourly data of the following variables:

- Date and time
- Global horizontal irradiance
- Direct normal irradiance
- Diffuse horizontal irradiance
- Dry bulb temperature (2m temperature)
- Air pressure
- Wind speed
- Wind direction (degrees clockwise from north)
- Relative humidity
- Long-wave downwelling infrared radiation" [20]

"The data set has been produced by choosing for each month the most "typical" month out of the full time period available e.g. 16 years (2005-2020) for PVGIS-SARAH2. The variables used to select the typical month are global horizontal irradiance, air temperature, and relative humidity." [20] The data that will be useful to estimate the wind turbines production is the date and time, the wind speed (at a 10-meter height), and, to a lesser extent, the wind direction (to determine in what direction the wind turbine(s) should be installed, following the algorithm results).

From the wind speed at 10 meters, the expected production of the wind turbines must be derived. For that, one has to convert the wind speed at 10 meters to the wind speed at the wind turbine's height, 30 meters, for example. The wind goes faster as the height increases (in general). The formula used is the one proposed by Vincent Kelner in his course at Helmo Gramme:

$$\text{the wind speed at the wind turbine's height} =$$

$$\text{wind speed at 10 m} \times (\text{wind turbine's height (30 m)} / \text{height of 10 m})^{\text{ground roughness coefficient}}$$

For this project, Broptimize suggested a value of 0.2 for the ground roughness coefficient because it corresponds to the reality of most places in Belgium, except for the coast and the sea. The highest the ground roughness coefficient is, the more what surrounds the wind turbine considerably slows the wind.

With the wind speed at the wind turbine's height, it is possible to compute its expected production thanks to its power curve. This curve represents the theoretical production of a wind turbine given the wind speed (in m/s). It is always equal to 0 for small wind speed values before growing exponentially (cubic function) to reach a plateau at the nominal power of the wind turbines. When the wind speed is too high, wind turbines go into safe mode, stop, and do not produce anymore. This is applied later in this report with the specific data on wind turbines.

3.1.2 Estimating solar panel production

For the hourly radiation data, "the solar radiation data used by PVGIS consists of one value for every hour over a multi-year period. This tool gives the user access to the full contents of the solar radiation database. In addition, the user can also request a calculation of PV energy output for each hour during the chosen period." [20] In the model, one of the decision variables will be the peak power in kWp [1] of solar panels installed.

With PVGIS, the hourly radiation data of the last few years for 1 kWp of solar panels is available. To compute the expected solar panel production, the idea is to compute the mean annual production of the last six years since 2020 [2](2015-2020). Then, multiply the hourly production of one reference year (e.g., 2020) by the ratio "mean annual production over the 2020 annual production". This will give the expected hourly production of 1kWp of solar panels. To obtain the expected hourly production of x kWp, the algorithm has to multiply by x the data for 1 kWh.

3.2 Description of the electric production solutions

3.2.1 Characteristics of wind turbine models considered

Three models of wind turbines will be available for the algorithm:

- Fairwind F180 (nominal power: 55 kW, height: 32m); [21]
- Eocycle M26 (nominal power: 90 kW, height: 38m); [22]
- EWT DW61 (nominal power: 499kW, height: 55m). [23]

Many more wind turbine models are available, but these three are models Broptimize's suppliers work with and are significantly different in terms of nominal power and height. Table 3.1 gathers some other characteristics of these wind turbines. The prices are the most recent ones Broptimize could provide, but they are increasing with the current inflation. For a wind turbine installation, one needs a license depending on the nominal power of the wind turbine. For this project, it will be assumed that all the necessary licenses are obtained.

[1] The Wp (Watt-peak) is based on a standard that corresponds to the maximum electrical power supplied by a solar panel under standard temperature and sunlight conditions. This is a theoretical value.

[2] More recent data is not available yet on PVGIS.

	Fairwind	Eocycle	EWT
Installation price	200,000€	435,000€	1,750,000€
License price	4,000€	4,000 €	25,000€
Annual operational costs	4,000€	4,000 €	23,000€

Table 3.1: Characteristics of the three models of wind turbines considered

Figures 3.3, 3.4, and 3.5 [3], represent the power curves of the three wind turbines that were used to compute the expected production given the wind speed at the wind turbine's height, as explained above. Regarding the degression of the efficiency as time goes by, Broptimize usually takes a value of 0.8% per year for their analyses. Normally, the technical specifications sheet indicates it, but it is not always the case, and the values are generally close to 0.8%, so this seems a good approximation.

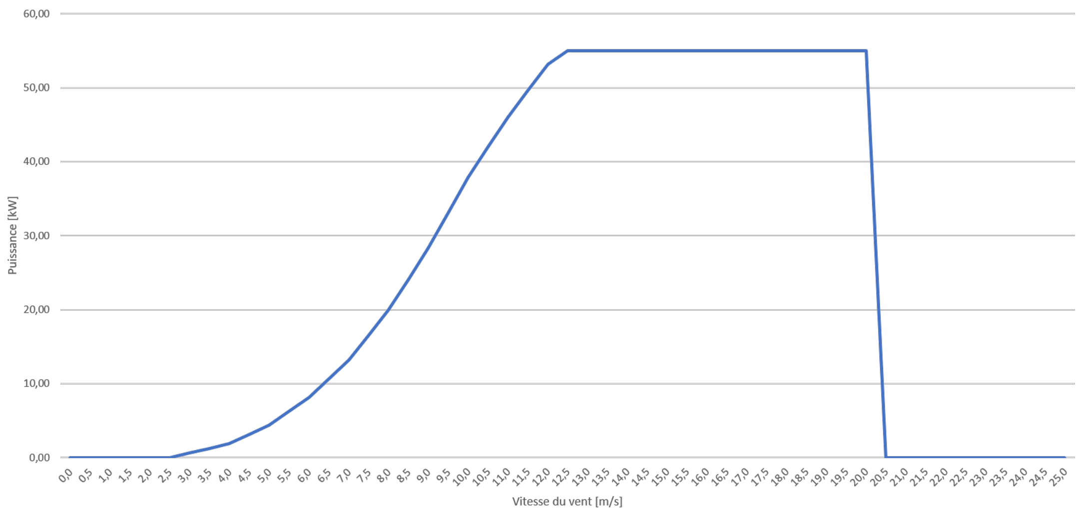

Figure 3.3: Power curve for the 55 kW wind turbine

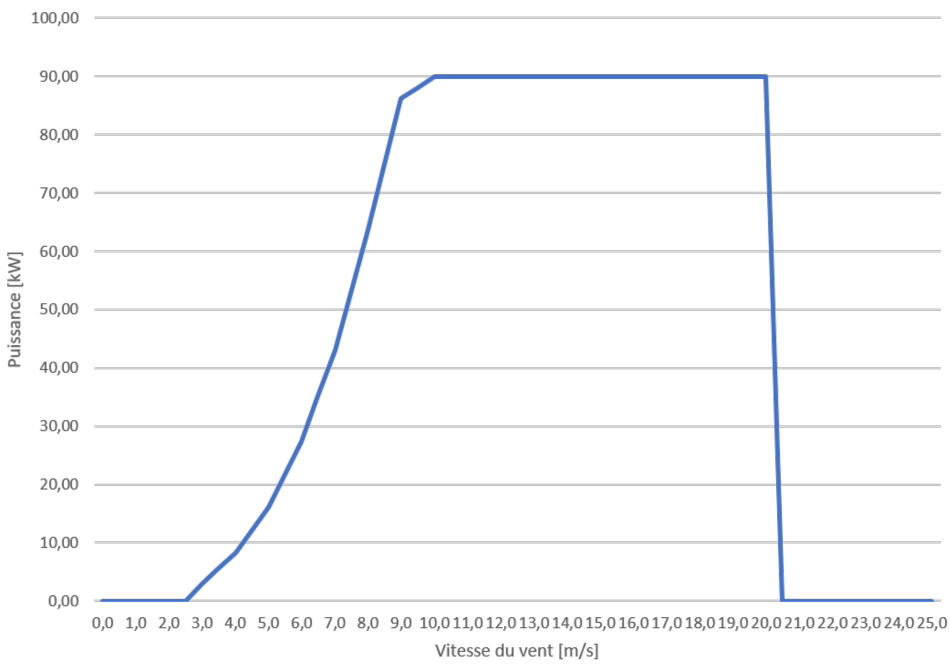

Figure 3.4: Power curve for the 90 kW wind turbine

[3]These power curves were provided by Broptimize but are also generally available in the technical documentation of each model.

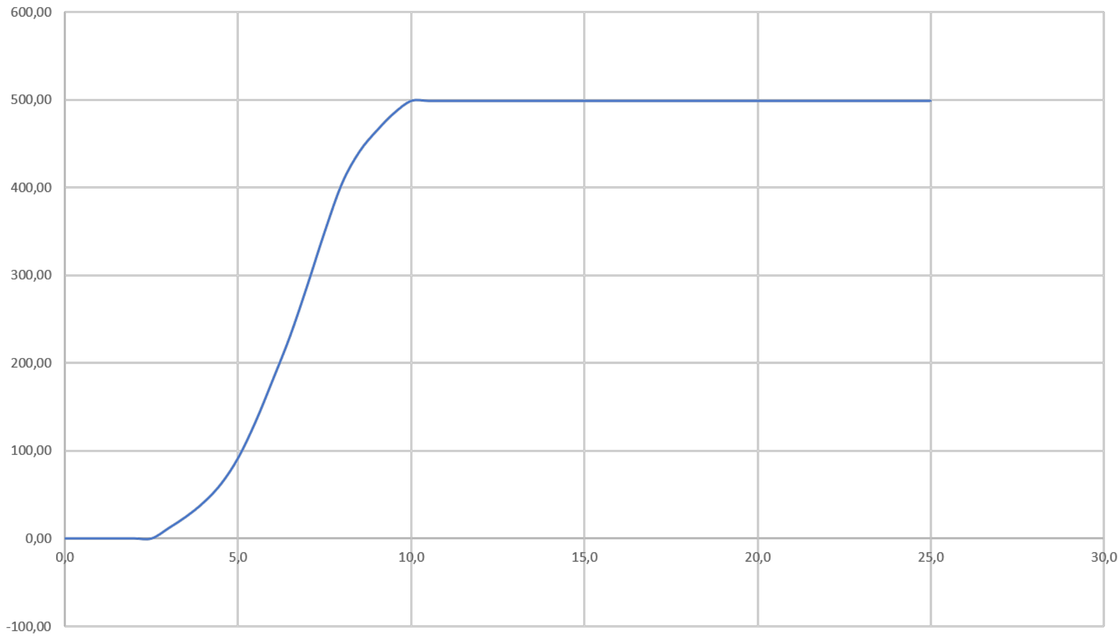

Figure 3.5: Power curve for the 499 kW wind turbine (production in kW with respect to the wind speed in m/s

For wind turbines, there are investment incentives of 20% of the investment costs for SMBs and 10% for large companies. In addition, there is 13.5% tax deductibility for the investments for companies.

3.2.2 Characteristics of solar panel model considered

For solar panels, it is important to know the area available for their installation, the slope of the roof (flat roof or not), the orientation, the shade, etc., to predict the production. If the roof is flat, the solar panels must be installed inclined and with space between rows not to overshadow each other, as shown in Figure 3.6 (left) [4]. If the roof is inclined, the solar panels can be installed right next to each other on the whole roof, except at the roof's edge, as shown in Figure 3.6 (right) [5]. This impacts the peak power of solar panels that can be installed per m^2 of the roof.

Figure 3.6: (Left) Solar panel installation on a flat roof, (Right) Solar panel installation on an inclined roof

[4]source: https://www.energreen.be/wp-content/uploads/2021/05/installation-panneaux-solaires-toit-plat-energreen.jpg

[5]source: https://cdn.hellowatt.fr/media/uploads/zinnia/2020/02/13/combien-panneaux-solaires-toit.jpg

In general, the nominal power of one solar panel is around 400 Wp; technical specifications sheets can be found on Alma Solar's website [24] for example. The dimensions of one standard solar panel are roughly 171cm × 113 cm × 3 cm. The degression of the efficiency is around 0.5% per year during the lifetime of the panels ($\geq$ 15 years for most). The prices for one solar panel vary depending on the supplier, the manufacturing country, the size of the installation, ... For 2023, Broptimize has made hypotheses on the price per Wp installed that take into account the side costs such as the cables based on the quotations the company receives for its clients. These prices are shown in Table 3.2.

Size of the installation	Price per Wc installed (Excl. VAT)
[0 - 10 kWc]	1.2 €/Wc
]10 - 30 kWc]	1.1 €/Wc
]30 - 50 kWc]	0.95 €/Wc
]50 - 100 kWc]	0.9 €/Wc
]100 - 150 kWc]	0.85 €/Wc
]150 - 200 kWc]	0.8 €/Wc
]200 - 250 kWc]	0.75 €/Wc
]250 - 350 kWc]	0.7 €/Wc
]350 - 500 kWc]	0.65 €/Wc
]500 - 1000 kWc]	0.55 €/Wc
$>$ 1000 kWc	0.5 €/Wc

Table 3.2: Price hypothesis for different sizes of solar panel installation in 2023

Another important element in a solar panel installation is the inverter and its nominal power. An inverter transforms the direct current produced by the solar panels into alternating current for the electricity to be used on a daily basis. The nominal power and the type of inverter are important because they impact the solar panels' electricity production and performance.[25] The type of inverter should depend on the complete installation's complexity, storage batteries' existence, etc.

Hybrid inverters are the most recent type of inverter and are intelligent.[25] They can determine which source of electricity should be used or stored. This is probably the most suitable type of inverter for the projects analyzed in this report. In general, the nominal power of the inverter should be around 80% total power of the solar panel installation; a too-high nominal power of the inverter decreases the yield of the installation. A well-sized inverter allows producing more and better and will extend the life of the solar panel installation.[26]

3.2.3 Characteristics of the cogeneration plants considered

Cogeneration plants are interesting because they combine heat and electricity production with a very high yield. Solar panels have their highest productivity during sunny and not-too-hot days when heat needs are generally low. On the contrary, solar panels generally produce little during winter (because of the more frequent rain or snow), and the heat needs are more significant. Therefore, cogeneration plants could produce electricity and heat, which would have to be produced anyway, thus avoiding using the generator. The sizing algorithm does not monitor or consider heat consumption, so there is no heat demand constraint to satisfy. Still, one can reasonably assume there will be a heating need, especially during winter. However, if the heat need is always null or very low, one could constrain the algorithm not to propose any cogeneration plant because there will be no need for its heat production.

For the algorithm, it was impossible and of little interest to encode all the existing cogeneration plants as possibilities. The range of XRGI cogeneration plants from EC Power [27] is the one chosen to be in the algorithm. Their respective power is significantly different, and if needed, these cogeneration plants can be combined to increase the maximum production. One of them is supplied with biogas instead of gas, which can reduce the CO_2 emissions.

Table 3.3 gathers the main characteristics of the cogeneration plants that will be proposed to the sizing algorithm. They mainly come from the technical specifications sheets available on the Website [27]. The values indicated for the maximum gas consumption are according to the lower calorific value of gas, which is the type of calorific value generally considered in Europe. [28]

	XRGI 6	XRGI 9	XRGI 15	XRGI 20	XRGI 15 Biogenic
Price	32000€	38000€	50000€	58000€	60000€
Type gas	gas	gas	gas	gas	biogas
Conso gas max	20 kW	30.5 kW	48.1 kW	61.1 kW	49.6 kW
Prod elec max	6 kW	9 kW	15 kW	20 kW	14.5 kW
Prod heat max	14.4 kW	23.3 kW	35.9 kW	44.7 kW	36.7 kW
Operational costs	0.77€/h	0.82€/h	1.17€/h	1.17€/h	1.17€/h
Mean conso elec	0.03kW	0.07kW	0.054 kW	0.054 kW	0.047 kW

Table 3.3: Characteristics of the five models of cogeneration plants considered

3.3 Description of the five studied cases

This project is based on analyzing a sizing algorithm's application on five cases provided by Broptimize. This section aims to describe these five cases. They are denoted by general terms (Hypermarket, Supermarket, Concrete producer, Sawmill, and Potato grower) referring to their business activity to anonymize their data. They are all located in the Walloon region in Belgium.

The electrical demand and the estimated solar panel and wind turbine production will be described for each case. The electrical demand data comes from Broptimize. The load duration curves of the electrical demand are generated thanks to an adaptation of the code explained in [29]. The load duration curve is defined as the curve between the load and time in which the ordinates representing the load, plotted in the order of decreasing magnitude, i.e., with the greatest load at the left, lesser loads towards the rights and the lowest loads at the time extreme right."[30] The solar panel and wind turbine productions are respectively derived from the hourly radiation data and the typical meteorological year data available in the PVGIS database [20].

3.3.1 Hypermarket

Demand data

The Hypermarket case has a relatively constant demand profile over the year, as shown in Figure 3.7. There is a slight increase in the electrical demand in summer, likely due to a more important need for air-conditioning the building. The yearly electrical consumption is roughly 800MWh. The hypermarket is open only during the day. The demand during working hours is the most significant, but there is still some demand during the night, to power the fridges for example. In Figure A.1 in the appendices, one can see that the hourly demand seldom goes below 50kWh. One can suppose that this alternation between day and night demand is what is visible in Figure 3.8, with the load duration curve "split" into two parts.

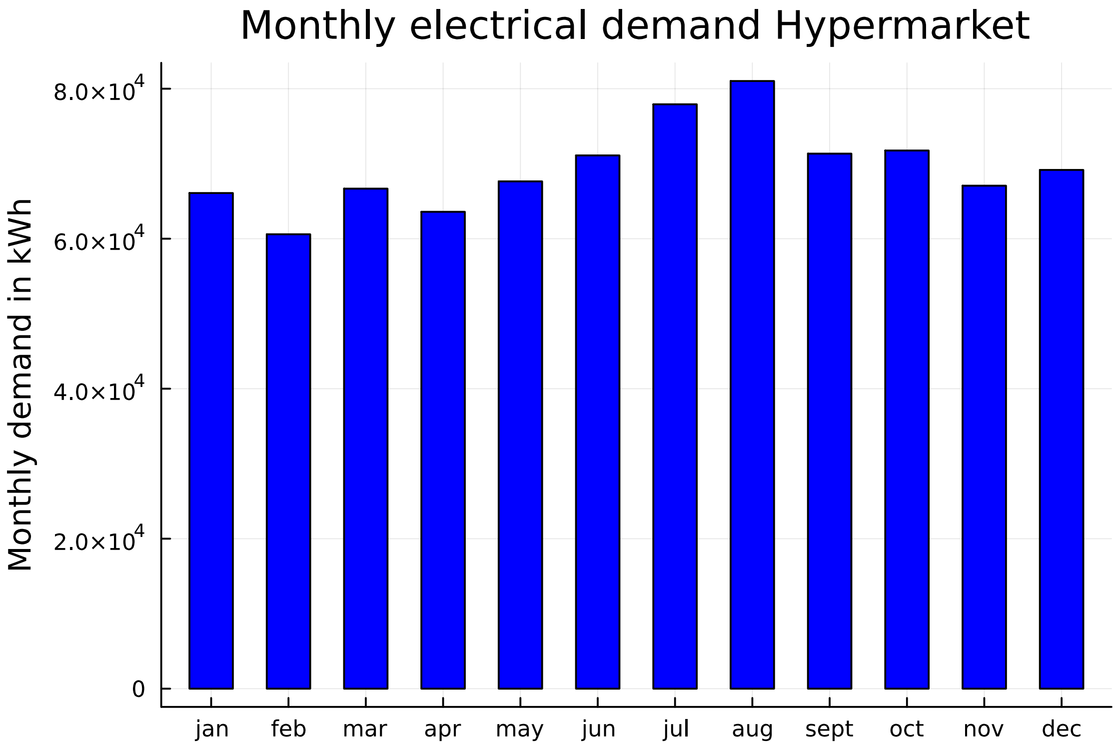

Figure 3.7: Bar plot of the monthly electrical demand for the Hypermarket case

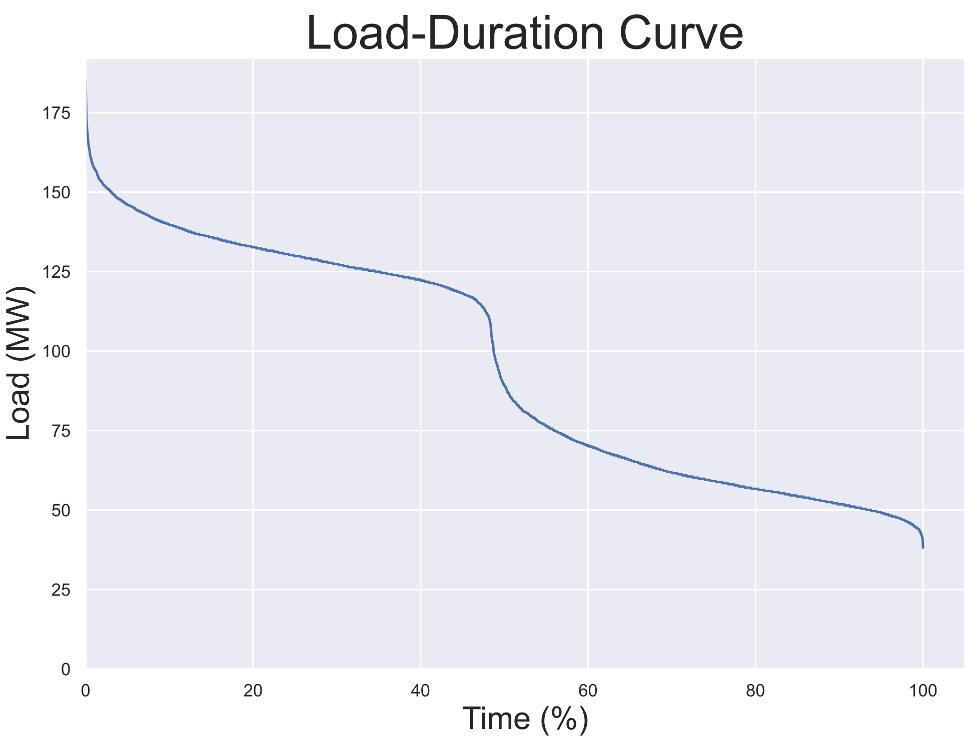

Figure 3.8: Load duration curve of the electrical demand for the Hypermarket case

Wind turbine production data

Figure 3.9 shows the monthly expected production of wind turbines for a typical meteorological year at the Hypermarket location. The production during autumn and winter is superior, but this is generally the case in Belgium. The five cases' monthly wind turbine production graphs differ because the operating conditions of wind turbines vary more locally, while the solar panel production graphs are fairly similar.

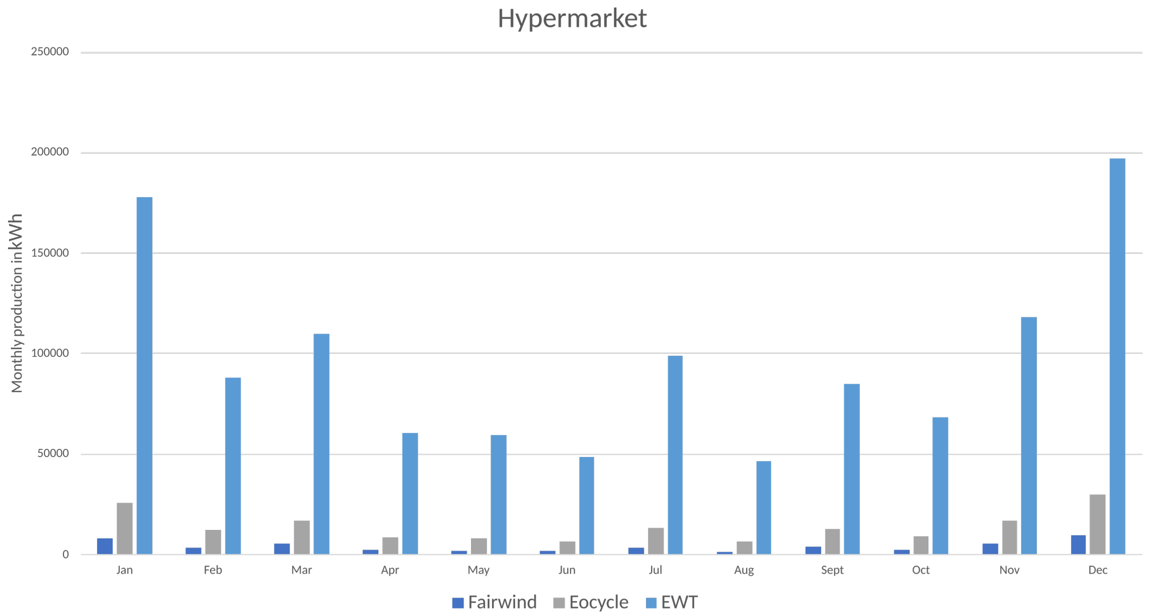

Figure 3.9: Monthly production for the three models of wind turbines at the Hypermarket localization

Solar panel production data

As it is the case for the great majority of the years, solar panel production is the highest during spring and summer. This solar data from PVGIS are those of 2020, marked by a very sunny spring, which is why April and May's productions are very high. However, one year is not another, and the solar irradiance may vary a lot, especially with climate change more and more impacting. The graph in Figure 3.10 shows an expectation of the production of 1 kWp of solar panels and, therefore, one will assume that the following years will be more or less similar for the sake of simplicity. The same reports can be made for the five cases.

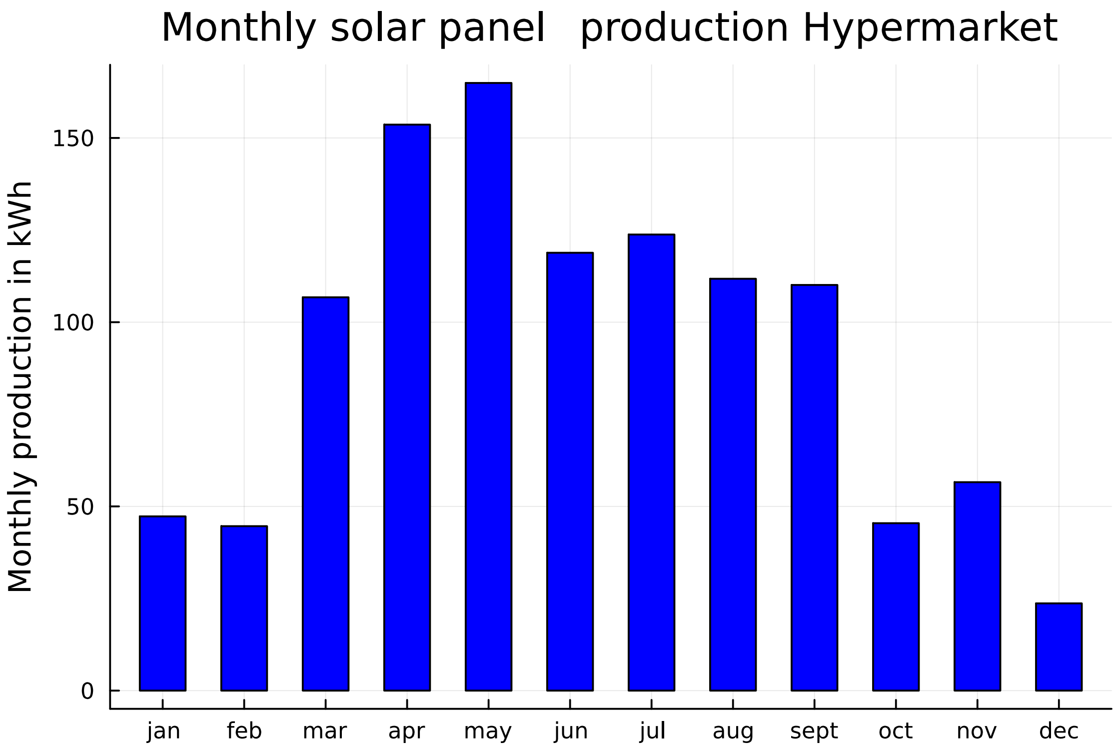

Figure 3.10: Monthly production for 1 kWp of solar panels at the Hypermarket localization

3.3.2 Supermarket

Demand data

The Supermarket case is very similar to the Hypermarket one in terms of the structure of the electrical demand, although the yearly electrical consumption is around 300MWh and not 800MWh. It is constant over the year, as shown in Figure 3.11. There is also a slight increase in the electrical demand in summer, likely due to a more important need for air-conditioning the building. Similarly, the load duration curve (Figure 3.12) looks "split" into two parts. The hourly demand can be seen in Figure A.2 in the appendices. One observation in this graph is equal to 0kWh but is likely an incorrect encoding or malfunction of the monitoring device. This null observation is behind the surprising shape of the end of the load duration curve.

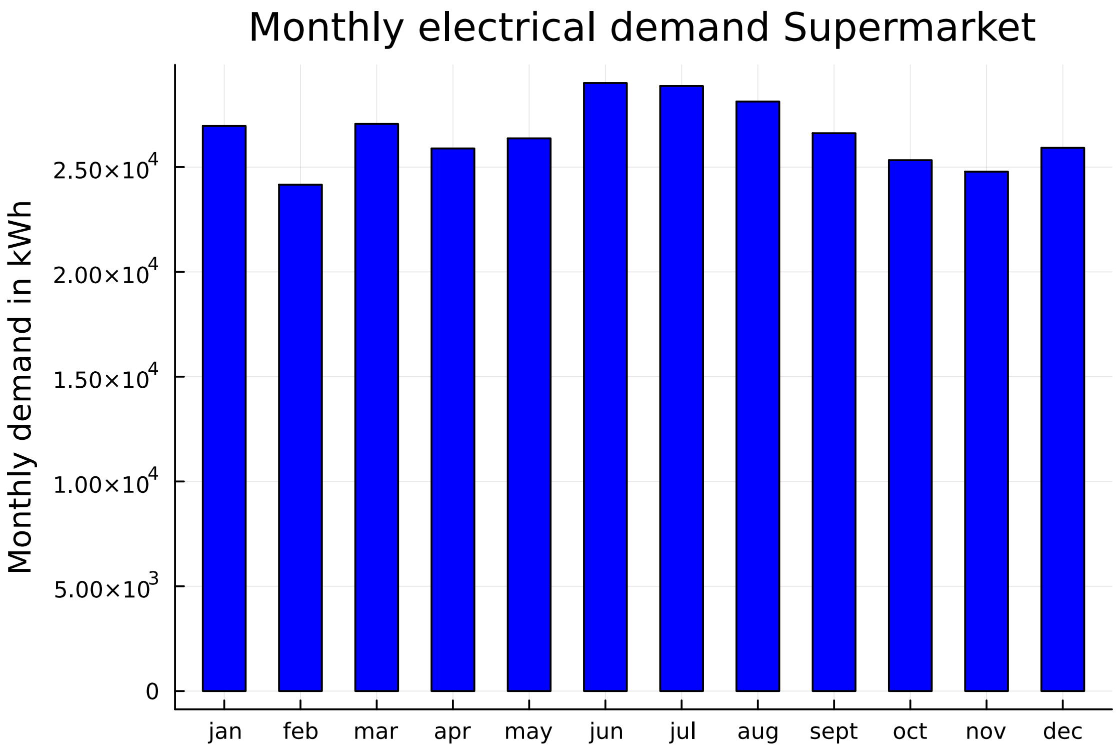

Figure 3.11: Bar plot of the monthly electrical demand for the Supermarket case

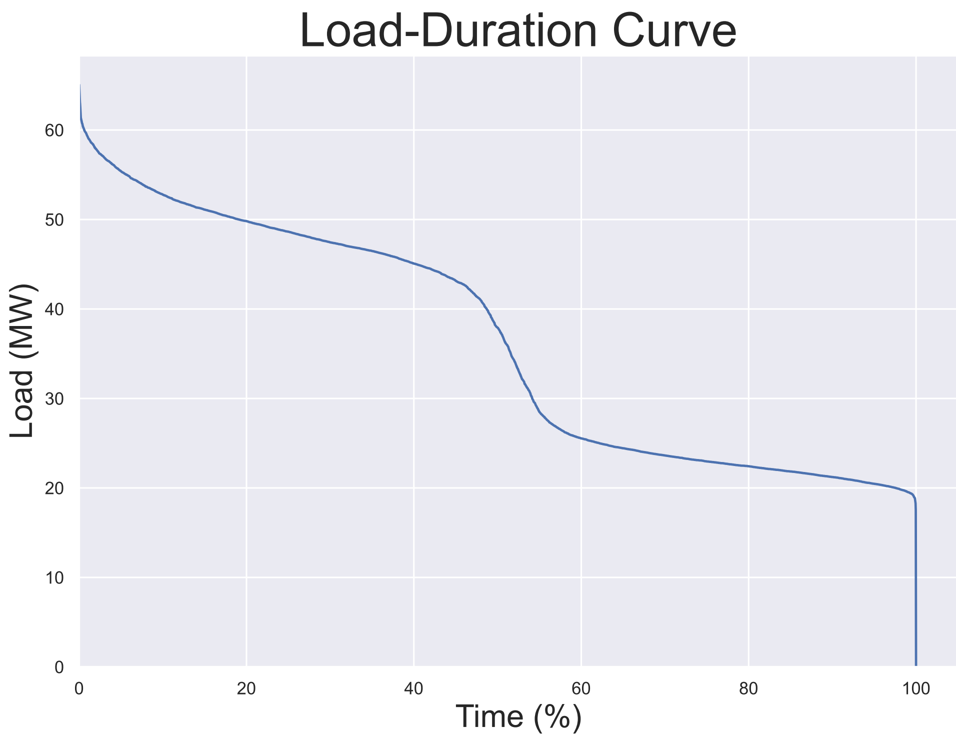

Figure 3.12: Load duration curve of the electrical demand for the Supermarket case

Wind turbine production data

Figure 3.13 shows the monthly expected production of wind turbines for a typical meteorological year at the Supermarket location. The production during the last three months of the year is significantly superior to the one of the other months.

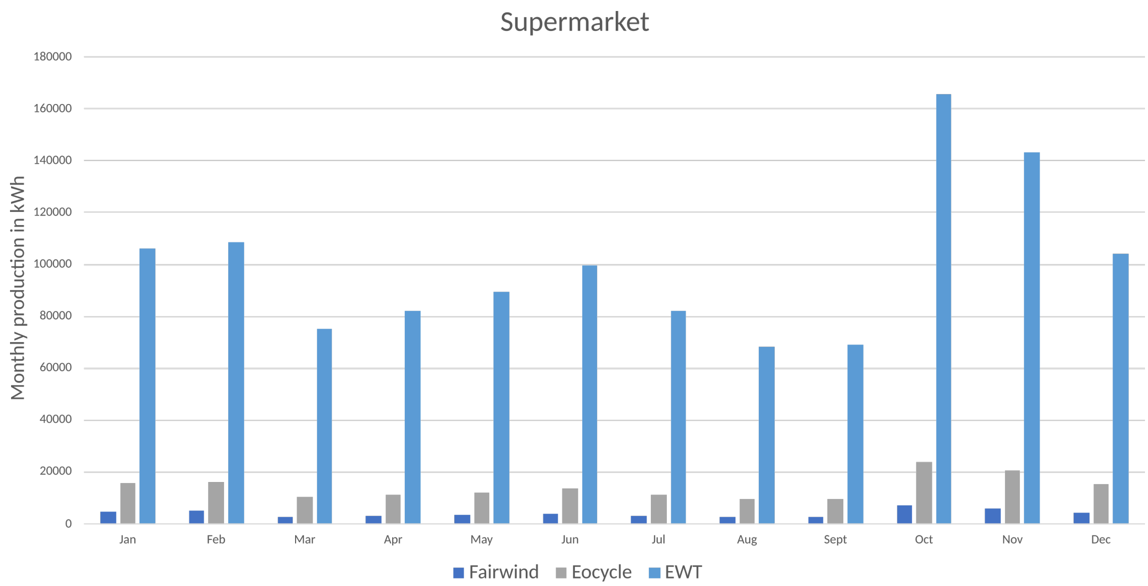

Figure 3.13: Monthly production for the three models of wind turbines at the Supermarket localization

Solar panel production data

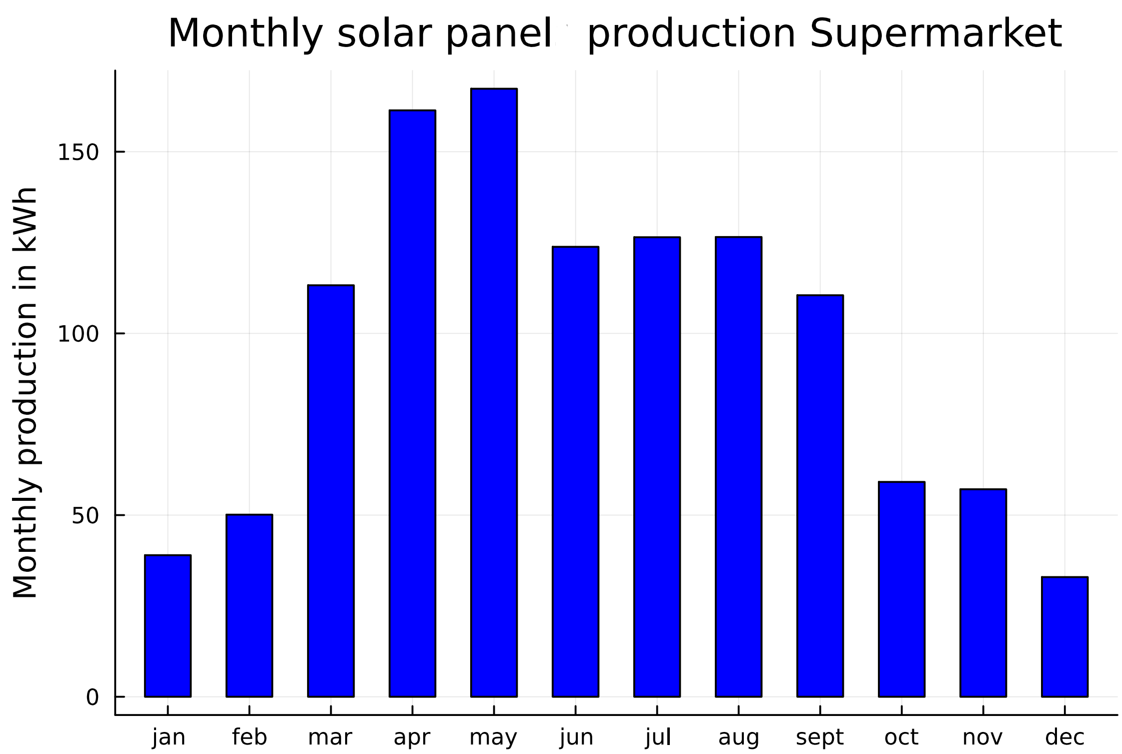

Figure 3.14: Monthly production for 1 kWp of solar panels at the Supermarket localization

3.3.3 Concrete producer

Demand data

The electrical demand for the concrete producer is significantly different from those of the Hypermarket and Supermarket and is around 70MWh per year. The difference is evident on the hourly electrical demand graph (Figure A.3. Electrical consumption is nearly zero during non-working hours (nights, weekends, and holidays in July, visible in Figure 3.15). This explains the shape of the load duration curve (Figure 3.16) with a majority of the hours (± 70%) with a very low load. This might impact the results of the sizing algorithm because the consumption periods correspond much more to the production periods, at least for the solar panels. Therefore, it is possible that the necessary battery capacity will be proportionally lower than the one for the Supermarket.

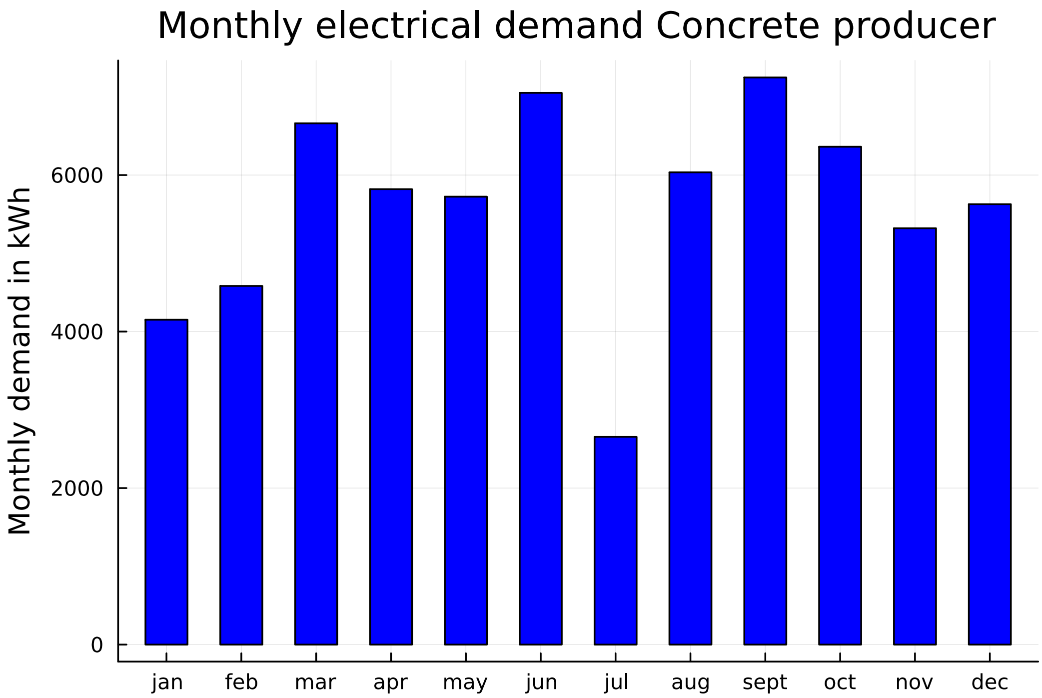

Figure 3.15: Bar plot of the monthly electrical demand for the Concrete producer case

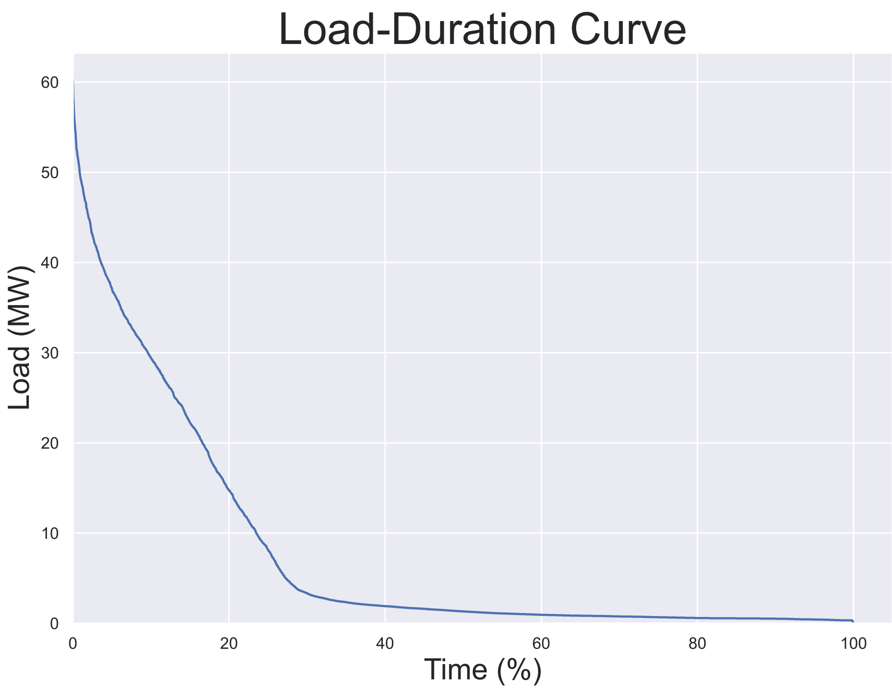

Figure 3.16: Load duration curve of the electrical demand for the Concrete producer case

Wind turbine production data

Figure 3.17 shows the monthly expected production of wind turbines for a typical meteorological year at the Concrete producer location. The production during December and January is significantly superior to the one of the other months.

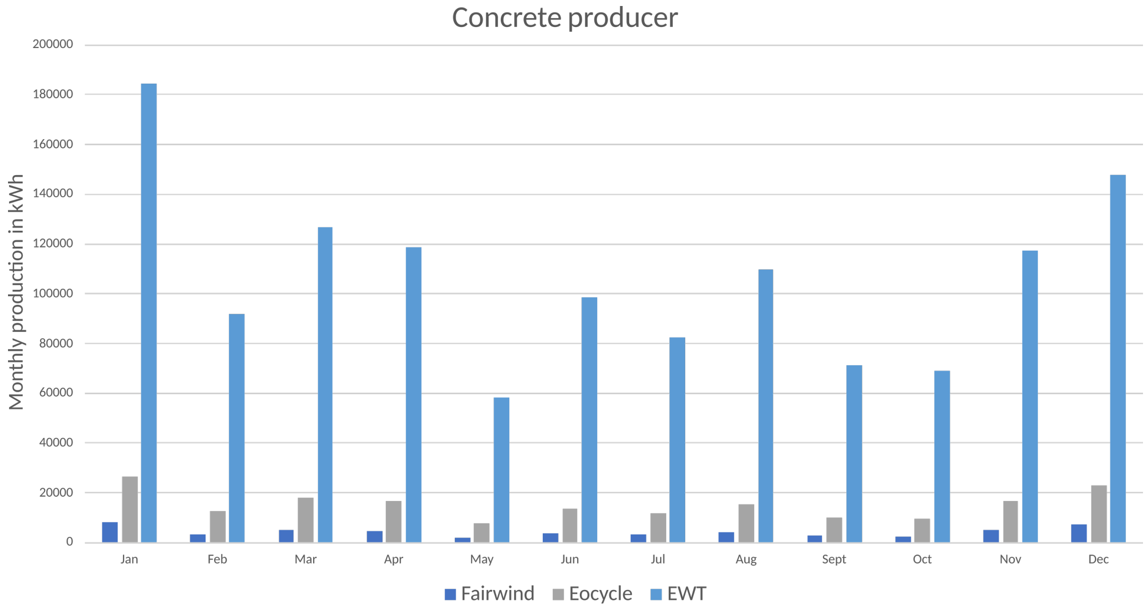

Figure 3.17: Monthly production for the three models of wind turbines at the Concrete producer localization

Solar panel production data

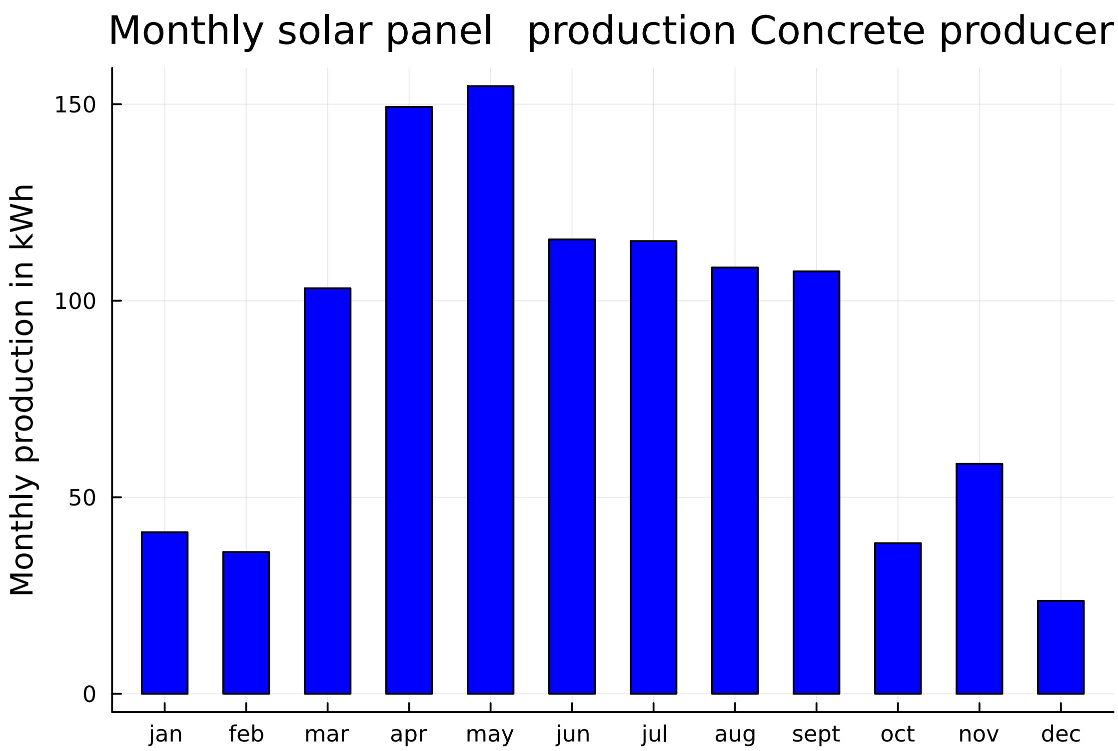

Figure 3.18: Monthly production for 1 kWp of solar panels at the Concrete producer localization

3.3.4 Sawmill

Demand data

The Sawmill case is the one with the highest electrical demand considered (around 3000MWh per year). This will enable us to compare the benefits of the different models of wind turbines with respect to the level of demand. The hourly electrical demand graph for the Sawmill (Figure A.4 in the appendices) is similar to the one of the Concrete producer with low (but not null) demand during the nights, the weekends, and the holidays in July. The majority of the demand is concentrated during the regular working hours. The load duration curve (Figure 3.20) shows that the demand for electricity is high only ± 40% of the time.

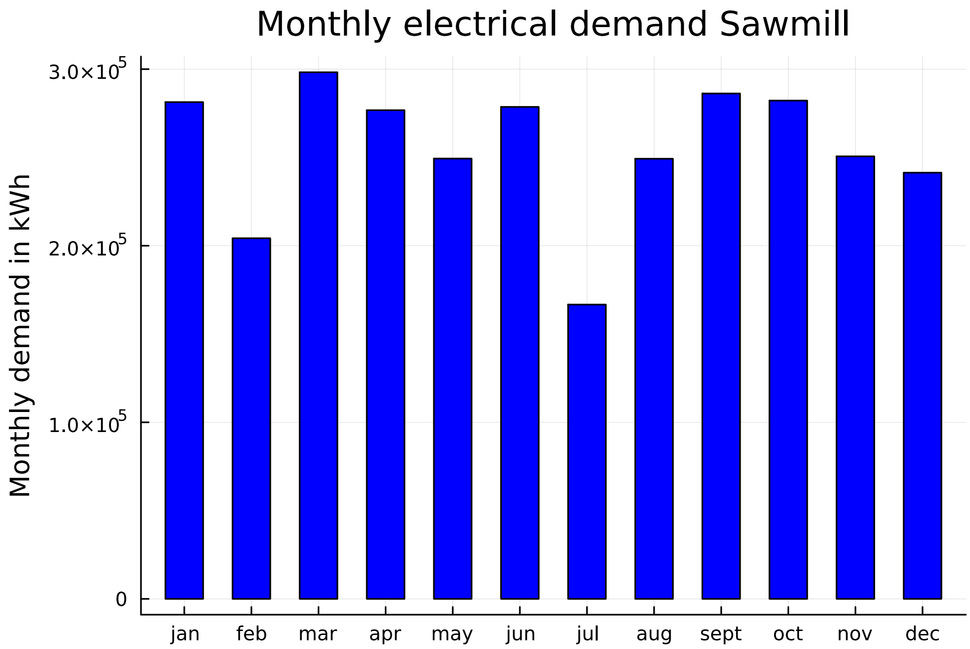

Figure 3.19: Bar plot of the monthly electrical demand for the Sawmill case

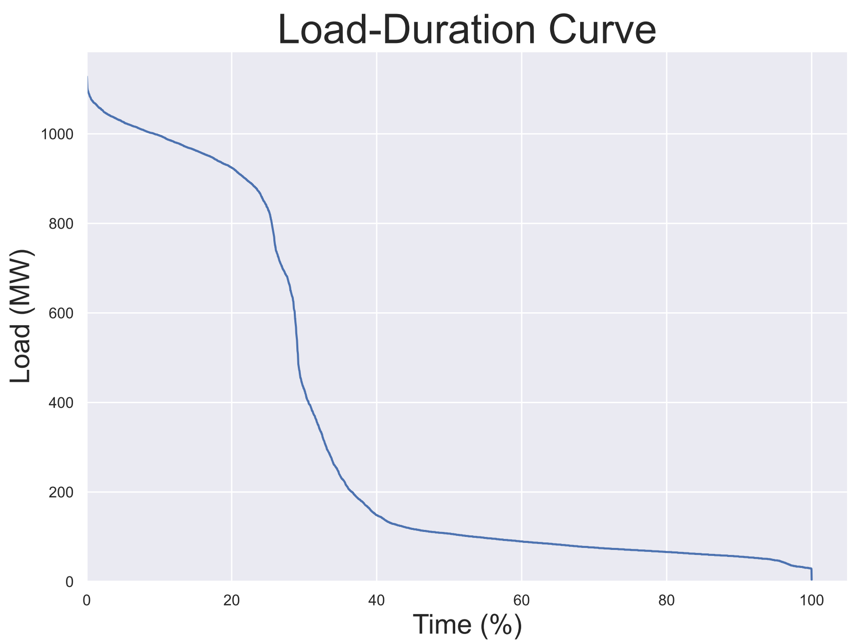

Figure 3.20: Load duration curve of the electrical demand for the Sawmill case

Wind turbine production data

Figure 3.21 shows the monthly expected production of wind turbines for a typical meteorological year at the Sawmill location. The production during October and January is the highest.

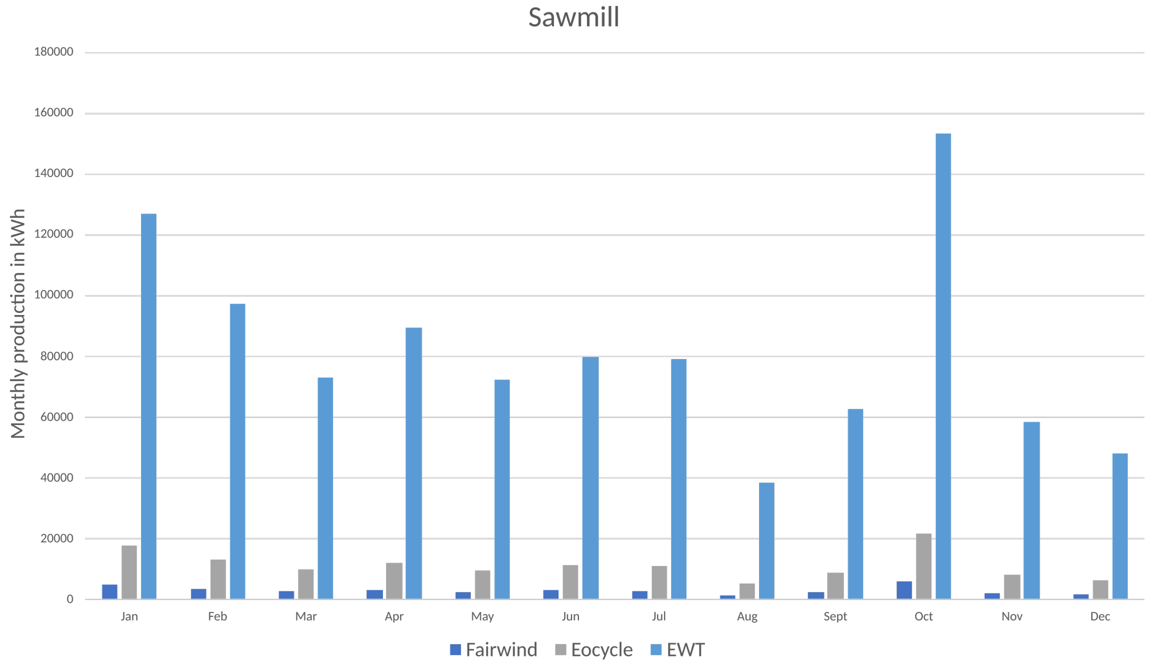

Figure 3.21: Monthly production for the three models of wind turbines at the Sawmill localization

Solar panel production data

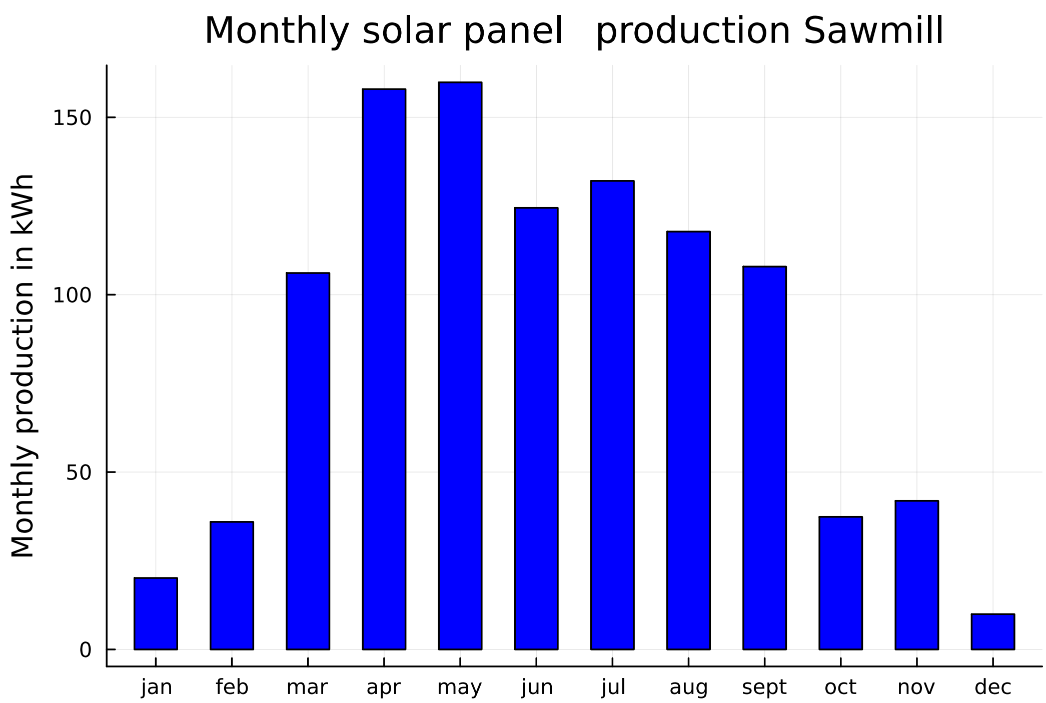

Figure 3.22: Monthly production for 1 kWp of solar panels at the Sawmill localization

3.3.5 Potato grower

Demand data

The electrical demand for the Potato grower is the lowest (around 25MWh per year), but it is also the most variable and atypical. This structure of demand shown in Figure 3.23 and Figure A.5 is linked to the requirements for an optimal potato harvest. As explained in [31], potatoes are generally harvested in September and October, depending on the weather. Then, they must be stocked in the dark at a temperature of 6°C with a controlled humidity level. These storage conditions are demanding in terms of electricity. Potatoes can be stored like that for up to 6 months, but the stocks will decrease over time with the sales, and thus the consumption. This case is challenging because, during the months with the highest solar panel production, the consumption is limited but is high during winter. Maybe a wind turbine will be more suitable than many solar panels.

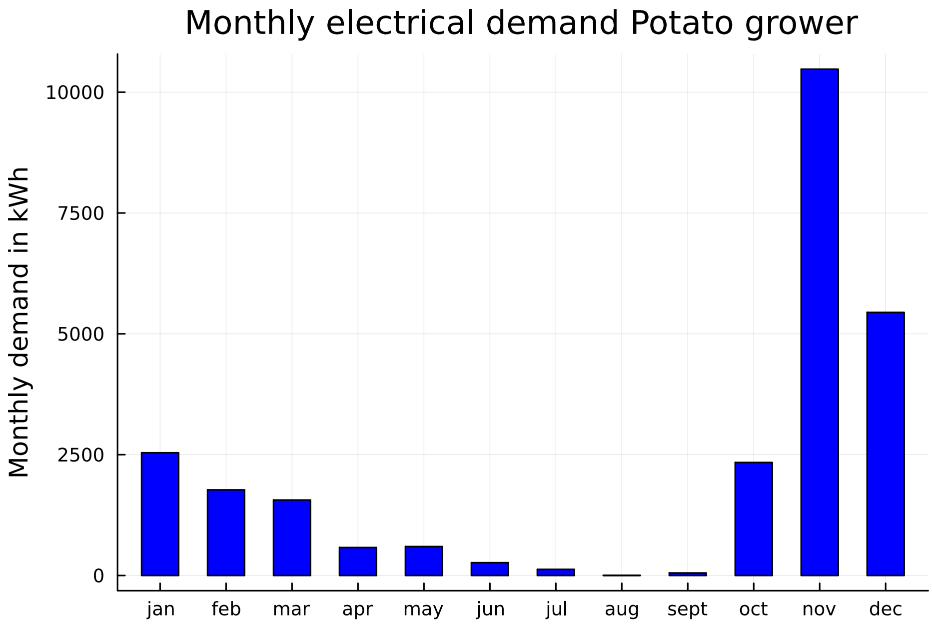

Figure 3.23: Bar plot of the monthly electrical demand for the Potato grower case

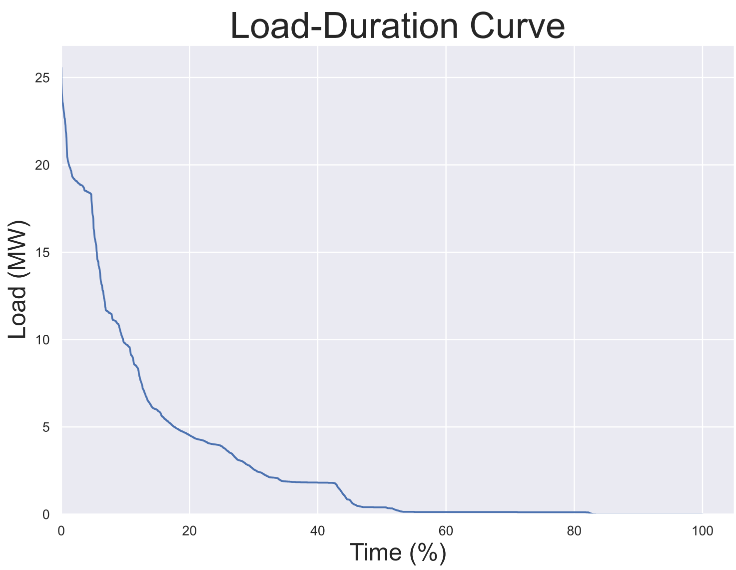

Figure 3.24: Load duration curve of the electrical demand for the Potato grower case

Wind turbine production data

Figure 3.25 shows the monthly expected production of wind turbines for a typical meteorological year at the Potato grower location. The production during autumn is the highest, corresponding to the months with the highest electrical demand.

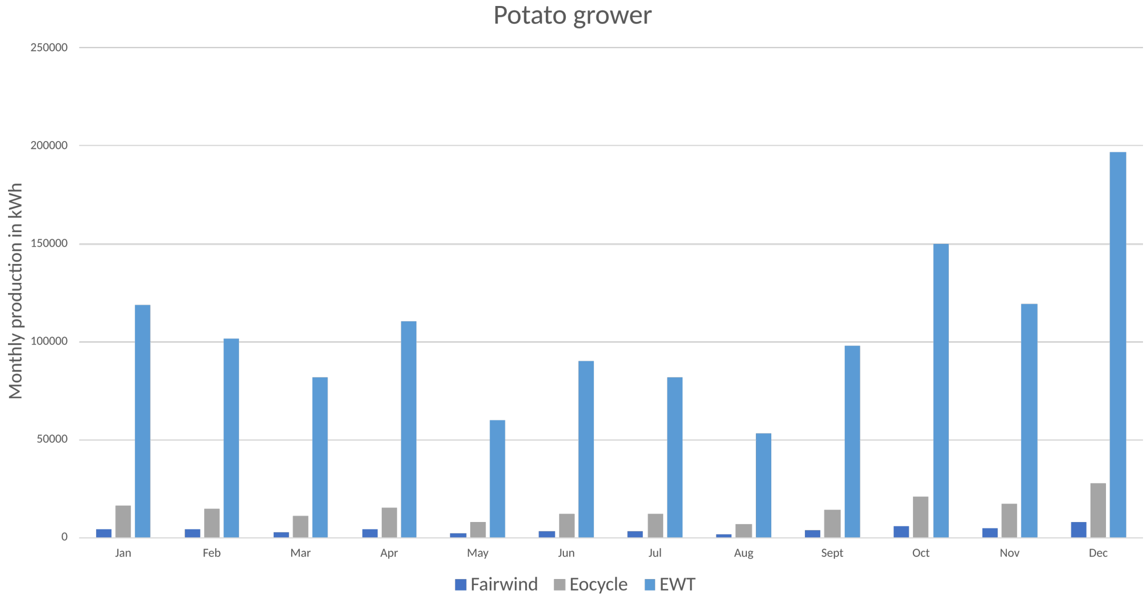

Figure 3.25: Monthly production for the three models of wind turbines at the Potato grower localization

Solar panel production data

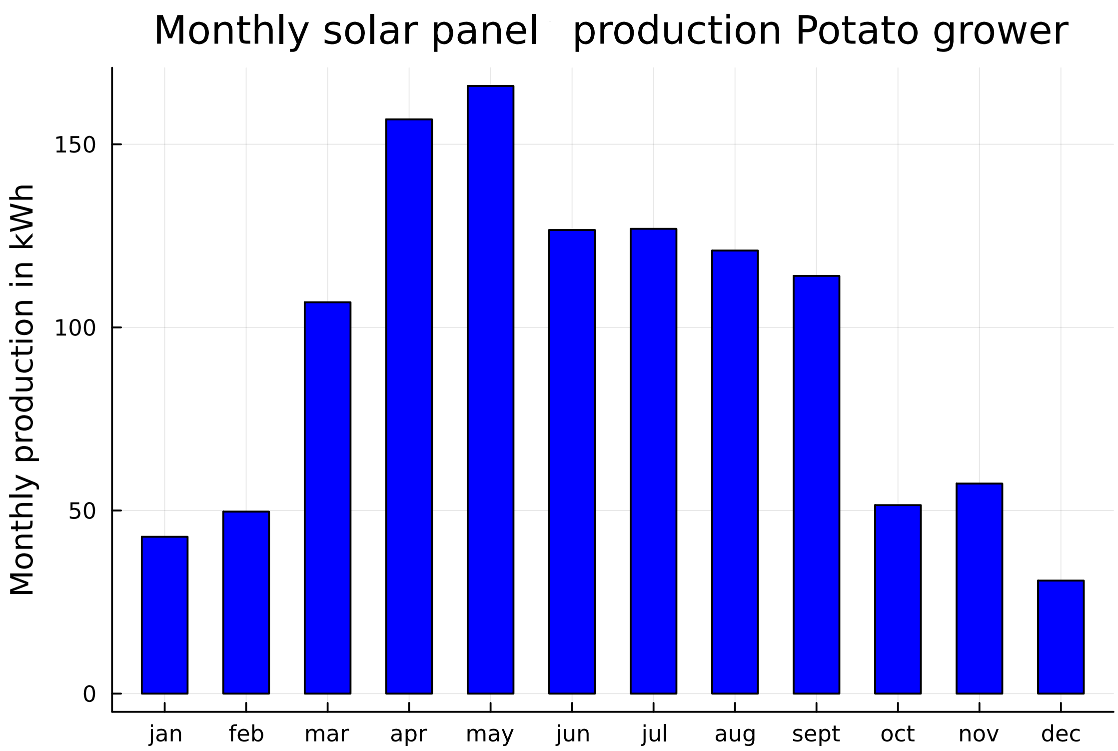

Figure 3.26: Monthly production for 1 kWp of solar panels at the Potato grower localization

3.4 Selection of representative days

To build the model with the representative days, some days must be selected for each case. The goal is, indeed, to reduce the size of the amount of data to deal with while minimizing the loss of information. For each of the five cases, 12 days of the demand datasets have been selected thanks to the code of Sébastien Mathieu available in his GitHub [18]. The purpose of his code is to extract a given number of representative days of a set of time series. Table 3.4 gathers the 12 representative days for each case and their respective weight.

Hypermarket		Supermarket		Concrete producer		Sawmill		Potato grower	
n°day	weight	n°day	weight	n°day	weight	n°day	weight	n°day	weight
13	13	9	8	13	35	13	30	13	13
45	34	44	55	45	28	45	18	45	2
53	8	95	68	53	5	53	7	53	25
58	6	152	21	58	7	58	32	58	211
72	11	209	28	72	27	72	33	72	5
115	10	216	5	115	8	115	39	115	11
141	7	221	4	141	9	141	56	141	3
156	92	265	63	156	49	156	20	156	12
191	5	331	53	191	14	191	7	191	35
303	14	344	20	303	26	303	76	303	4
328	137	354	18	328	155	328	31	328	29
347	28	365	22	347	2	347	16	347	15

Table 3.4: Selected demand representative days and respective weights for the five cases

One can notice that the selected days are the same for the five cases except for the Supermarket, although the associated weights are different.

Chapter 4

Formulation of the optimization problems

The section presents the models implemented and tested on the five cases provided by Broptimize to size production and storage solutions. First, the complete model is defined with the sets and indices used, the decision variables, the parameters and their values, the two objective functions, and the constraints to meet. Then, the adaptations to this model to build the one-year model and the model with representative days are described. Some variables, parameters, and constraints are inspired by Selmane Dakir's work on microgrid sizing, in particular in [32], [33], and [4].

4.1 Sets and indices

The different sets and indices that are used to define the variables and parameters of the optimization problems are listed below:

- y : the year index ($y \in [1, 2, 3, ..., Year]$) with $Year$ the number of years of the project.
- t : the time period index ($t \in [0, 1, 2, ..., T]$) with T the total number of time steps in the project (hours in this case);
- WT : set of the different types of wind turbines that are considered by the algorithm;
- SP : set of the different installations of solar panels that are conceivable for the project;
- $nbCogen$: set of the different cogeneration plants taken into account in the algorithm;

4.2 Decision variables

The reader can find below the list of variables of the optimization problem. The solver's goal is to assign a value to each of them so that the objective function is optimized. The variables are grouped to ease the reader's comprehension.

Variable relative to wind turbines

- X_i number of wind turbine of type i that must be installed for $i \in WT$.

Variables relative to solar panels

- $inverter_y$: the size of the inverter associated with the solar panel installations at year y [kW];
- $nbSP_{i,y}$: number of kWp of solar panels to be installed in installation i at year y for $i = 1, ..., SP$;
- $inputSP_t$: electricity obtained from the different installations of solar panels at time t, depending on the production of the solar panels and the size of the inverter(s) [kWh];

Variables relative to batteries

- $state_{Bt}$: state of charge of the batteries at time t [kWh];
- $size_B$: net size/capacity of the set of batteries to be installed [kWh];
- $charge_t$: electricity to put into the batteries at time t [kWh];
- $discharge_t$: electricity to remove from the batteries at time t [kWh];

Variables relative to cogeneration plants

- $instalCogen_i$: number of cogeneration plants of type i that must be installed for $i \in nbCogen$;
- $gas_{t,i}$: quantity of (bio)gas to consume at time t with one cogeneration plant of type i to produce x kWh of electricity with $i \in nbCogen$;

Variable relative to generator

- $fuel_t$: quantity of fuel to consume at time t to produce x kWh of electricity with the generator, NTP conditions [L];

Variables relative to finances

- I_y: investment costs for year y [€];
- O_y: operating costs for year y [€];
- R_y: revenues for year y [€];
- NPV: Net Present Value [€];

Variable relative to CO_2 emissions

- CO_2: sum over the project lifetime of the CO_2 emissions linked to the electricity production and storage solutions [g];

4.3 Parameters

Many parameters are involved in this model. They are listed below with a small description of their meaning.

Global parameters

- $Year$: number of years of duration of the project;
- T: number of time steps in the duration of the project (determined by the duration of the time steps and the number of years of the project);

Parameters linked to the electrical demand

- $demand_t$: demand of electricity at time t [kWh];
- $IncreaseDemand$: percentage of increase (or decrease) in demand for electricity over the years (could be not constant $\rightarrow IncreaseDemand_y \ \forall y = 1, ..., Year$);

Parameters linked to wind turbines

- $ProdWT_{it}$: production of the wind turbine i at time t [kWh] $\forall i \in WT$. This is computed in preprocessing thanks to the wind data coming from PVGIS. The production of wind turbines is assumed to be degraded by 0.8% per year;
- $OpCostWT_i$: yearly operational costs for wind turbine $i \ \forall i \in WT$ [€];

Parameters linked to solar panels

- $ProdSP_{it}$: production of one kWp of solar panels for installation i at time t [kWh] $\forall i \in SP$. This is computed in preprocessing thanks to the data coming from PVGIS. The production of solar panels is assumed to be degraded by 0.5% per year;
- $Area_i$: maximum number of kWp of SP that can be installed in installation i [kWp];

Parameters linked to batteries

- s_{B0}: initial state of charge of the batteries [kWh];
- $\eta^{discharge}$: efficiency of discharge of the set of batteries [%];
- η^{charge}: efficiency of charge of the set of batteries [%];

Parameters linked to cogeneration plants

- $ConsoMaxCogen_i$: maximum gas consumption for cogeneration plant $i \ \forall i \in nbCogen$ [kW];
- $PowerCogen_i$: maximum power of cogeneration plant $i \ \forall i \in nbCogen$ [kW];

- $ConsoMeanCogen_i$: average electricity consumption per hour for cogeneration plant i, computed by taking the mean of the consumption while the cogeneration plant is OFF and while it is ON, $\forall i \in nbCogen$ [kWh];
- $ConvertGas$: energy efficiency of an input of 1 kWh of gas in a cogeneration plant;
- $OpCostCogen_i$: operational costs per hour of use of cogeneration plant i $\forall i \in nbCogen$ [€];

Parameters linked to the generator

- $ConvertFuel$: conversion rate from an input of 1L of fuel/diesel in the generator and the number of kWh of electricity in output [kWh/L], corresponding to the lower heating value;
- $Penalization$: Penalizing factor for using one liter of fuel/diesel;

Financial parameters

- $BudgetMax$: the maximum budget that can be allocated to the project for the initial investment [€];
- $ReinvestMax_y$: the maximum amount of money that can be spent per year on reinvestment costs, operational costs, bills of fuels, ... [€] $\forall y = 1, ..., Year$;
- γ: discount factor [%];
- Prices:
  - $PriceB$: the price of one kWh of net battery capacity [€];
  - $PriceBioGas$: the price of one kWh of biogas [€];
  - $PriceCogen_i$: the price of one cogeneration plant of type i $\forall i \in nbCogen$ [€];
  - $PriceCV$: the price of reselling one green certificate [€];
  - $PriceFuel$: the price of one liter of fuel for the generator [€];
  - $PriceGas$: the price of one kWh of gas [€];
  - $PriceGen$: the price of the generator [€];
  - $PriceInverter$: the price of one kW of inverter [€];
  - $PriceSP_i$: the price of one kWp of solar panels for installation i [€];
  - $PriceWT_i$ $\forall i \in WT$: the price of one WT per type [€].

Parameters linked to CO_2 emissions

- CO_2 emissions linked to the electrical production for each technology:
  - $CO2B$: grams of CO_2 linked to the production of 1 kWh of net battery capacity;
  - $CO2biogas$: grams of CO_2 linked to the production of 1 kWh of electricity with biogas;

- $CO2fuel$: grams of CO_2 linked to the burning of 1 liter of diesel;
- $CO2gas$: grams of CO_2 linked to the production of 1 kWh of electricity with gas;
- $CO2SP$: grams of CO_2 linked to the production of 1 kWh of electricity with solar panels over its lifetime;
- $CO2WT$: grams of CO_2 linked to producing 1 kWh of electricity with wind turbines over its lifetime.

4.4 Value of the sets and the parameters

4.4.1 Values of the sets

The different sets used to define the variables and the parameters were presented in a previous section. Here, the values they take in this project are listed. The sets are relative to the electric production solutions considered in the algorithm: wind turbines, solar panels, and cogeneration plants. They were all described in the previous Chapter.

- WT: the set of wind turbines is composed of the Fairwind F180, the Eocycle M26, and the EWT DW61 (cardinality $WT = 3$);
- SP: for each of the five cases, there is only one possible installation of solar panels; therefore, the cardinality of SP is always 1 here;
- $nbCogen$: the set of cogeneration plants is composed of the five models of the range XRGI: XRGI 6, XRGI 9, XRGI 15, XRGI 20, and XRGI 15 Biogenic (cardinality $nbCogen = 5$).

4.4.2 Shared values among the five cases

Many parameters have a common value in all the cases. Those are listed with their value(s) below in the same order as the previous section to ease the reader's lecture.

- $Year = 15$. The lifetime of this type of project is generally around 15 years, sometimes a little more because it has to amortize the high costs of wind turbine and/or solar panel installation over their years of guarantee.
- $T = 131,400 = 24 \times 365 \times 15 = 8760 \times 15$ (24 hours $\times$ 365 days $\times$ 15 years). If the value 8760 is used in the definition of a variable or a constraint, it refers to the number of hours in a year ($8760 = 24 \times 365$).
- $IncreaseDemand$: 2%. It is supposed that the demand for electricity will increase due to global warming (more need for air-conditioning), a switch of the fleet car to electric vehicles, and the growth of the companies. With more precise data on the case and their expected evolution, this parameter could have been tailored and variable over the years.
- $OpCostWT$: [3000 €, 4000€, 23000€] (see Table 3.1);
- s_{B_0}: 0kWh. It is assumed that at the start of the project, the net electricity available in the batteries was null because the batteries were just installed.

- $\eta^{discharge}$: 98%. There is always a small loss when using electricity from batteries.
- η^{charge}: 98%. There is always a small loss when storing electricity in batteries.
- $ConsoMaxCogen$: [20 kW, 30.5 kW, 48.1 kW, 61.1 kW, 49.6 kW] (see Table 3.3)
- $PowerCogen$: [6 kW, 9 kW, 15 kW, 20 kW, 14.5 kW] (see Table 3.3)
- $ConsoMeanCogen$: [0.03kW, 0.07kW, 0.054kW, 0.054kW,0.047kW] (see Table 3.3)
- $ConvertGas$: $\frac{1}{3}$. Given the values of the maximum gas consumption of the five cogeneration plants and their maximum power, roughly 33% of the gas consumption is converted into electricity. The rest is converted into heat (not considered by the algorithm) with sometimes a total yield $\geq$ 100%.
- $OpCostCogen$: [0.77€, 0.82€, 1.17€, 1.17€, 1.17€] (see Table 3.3);
- $ConvertFuel$: 3 kWh/L. "A diesel generator will use 0.4 L of diesel per kWh produced as a rough rule of thumb" [34], so a value between 2.5 and 3 kWh/L seems reasonable (if considering that the technology improves).
- $Penalization$: 20, which means that the use of one liter of fuel will count as 20.
- γ: 1%. With the current crises, it is hard to forecast the evolution of inflation or exchange rate, so a small value for γ is taken not to influence the model too much.
- Prices:
  - $PriceB$: 800€, which is the average price to have 1 kWh of net capacity for a battery (pay attention to the discharge rate) on Alma Solar's website [24] for example.
  - $PriceBioGas$: 0.1€;
  - $PriceCogen$: [32,000€, 38,000€, 50,000€, 58,000€, 60,000€] (see Table 3.3);
  - $PriceCV$: 65€, which is the minimum guaranteed value for a green certificate.
  - $PriceFuel$: 1.7€;
  - $PriceGas$: 0.07€;
  - $PriceGen$: 500€$\times$ maximum electric demand during one hour. Using the generator should be avoided to reduce the CO_2 emissions. Still, its power should be sufficient to ensure a minimum operation in the event of a breakdown.
  - $PriceInverter$: 150€per kWh (see Alma Solar's website [24] for example);
  - $PriceSP$: [750€] (average price per kWp installed indicated in Table 3.2);
  - $PriceWT$: [204,000€, 439,000€, 1,775,000€] (installation price + license price) 3.1.

- CO_2 values:
  - $CO2B$: 100,000g per kWh installed (CO_2 emissions linked to the production of 1 kWh of batteries depend a lot on what is used to produce electricity to build the battery (coal, fuel, gas, renewable, ...) [35];
  - $CO2biogas$: 120g per kWh consumed ("On a life-cycle basis, biogas energy emits between 81 and 251 grams of CO2 equivalent per kWh of electricity produced" [36]);
  - $CO2fuel$: 2,600g per L consumed [37];
  - $CO2gas$: 490g per kWh consumed [38];
  - $CO2SP$: 45g per kWh produced (it is estimated that today, a solar panel emits on average 40 to 55 grams of CO_2 per kWh produced[39]. Naturally, it depends on the production condition of the solar panel; in China with coal-produced electricity or in Europe with renewable electricity [40].;
  - $CO2WT$: 14g per kWh produced (for on-shore wind turbines) (see Table [41]).

4.4.3 Specific values

Some values of parameters are specific to each case. The list below indicates the values of these parameters.

- $demand_t$: The electric demand is specific to each case and has already been described in the previous Chapter.
- $ProdWT_{it}$: The wind turbine production is specific to each case and has already been described in the previous Chapter.
- $ProdSP_{it}$: The solar panel production is specific to each case and has already been described in the previous Chapter.
- $Area_i$: The available space for solar panels is not the same in the different cases. In addition, some cases can install solar panels on a flat roof while the others have an inclined roof, with impacts the number of Wp that can be installed per m^2. For each case, there is only one possible installation. Table 4.1 gathers the different information related to the space available.

Case	Hypermarket	Supermarket	Concrete producer	Sawmill	Potato grower
Available space	$2,300m^2$	$1,100m^2$	$800m^2$	$9,000m^2$	$1,000m^2$
Roof orientation	flat	flat	inclined	inclined	inclined
Possible kWp/m^2	0.13	0.13	0.2	0.2	0.2
Area (max kWp installed)	299kWp	143kWp	160kWp	1800kWp	200kWp

Table 4.1: Data linked to the computation of the parameter $Area$ for the five cases

- $BudgetMax$: Not to have an infeasible optimization problem or bad results due to a too restrictive budget, $BudgetMax$ has been set to be more than enough. Depending on the level of demand, this budget is not in the same order of magnitude in the five cases.

Case	Hypermarket	Supermarket	Concrete producer	Sawmill	Potato grower
$BudgetMax$	10,000,000€	5,000,000€	2,000,000€	75,000,000€	3,000,000€

Table 4.2: Values for the maximum budget for the five cases

- $ReinvestMax$: As for $BudgetMax$, not to have an infeasible optimization problem or bad results due to a too restrictive budget, $ReinvestMax$ has been set to be more than enough. Depending on the level of demand, this budget is not in the same order of magnitude in the five cases.

Case	Hypermarket	Supermarket	Concrete producer	Sawmill	Potato grower
$ReinvestMax$	1,000,000€	500,000€	400,000€	5,000,000€	400,000€

Table 4.3: Values for the maximum reinvestment budget for the five cases

4.5 Objective functions

4.5.1 NPV

$$\max NPV$$

This objective function, mathematically defined in the Decision Variables section, maximizes the project's Net Present Value while financially penalizing fuel use.

4.5.2 CO_2

$$\min CO_2$$

Minimizing the CO_2 objective function tries to minimize the CO_2 emissions linked to the project during its complete lifetime.

4.5.3 Combined

$$\max NPV - (CO_2/1,000,000) * 100$$

This last objective function aims to link the two previous objective functions. For that, the CO_2 emissions are converted into money. The chosen price for one ton of CO_2 is 100€, which aligns with the temperature targets set out in the Paris Agreements. Since the CO_2 variable is expressed in grams, it has to be divided by 1,000,000 to correspond to tons of CO_2. This objective function has been applied to the one-year and representative days models but not to the complete one.

4.6 Constraints

- The demand for electricity must be met at each time step:

$$demand_t + \sum_{i \in nbCogen} (ConsoMeanCogen_i * instalCogen_i) = inputSP_t$$

$$+ \sum_{i \in WT} (ProdWT_{t,i} * X_i) + discharge_t * \eta^{discharge} - charge_t$$

$$+ \sum_{i \in nbCogen} (gas_{t,i} * instalCogen_i * ConvertGas) + fuel_t * ConvertFuel \ \forall t = 1, ..., T$$

The demand (and the electrical consumption of the cogeneration plants installed) must be ensured thanks to the production of solar panels and wind turbines, the electricity stored in the batteries, the electrical production of cogeneration plants, and, if needed, the generator. In case the production of solar panels and wind turbines is superior to the demand at a certain time step t, the system can store this surplus in the batteries for later.

- The electricity coming from the solar panels is at the maximum equal to the minimum between the size of the inverter and the sum of the production of each solar panel:

$$inputSP_t \leq \sum_{i \in SP} (ProdSP_{t,i} * nbSP_{i,1+\lfloor \frac{t-1}{8760} \rfloor}) \; \forall t = 1, ..., T$$

$$inputSP_t \leq inverter_{1+\lfloor \frac{t-1}{8760} \rfloor} \; \forall t = 1, ..., T$$

- Max x wind turbines of each type (e.g., $x = 2$):

$$X_i \leq x \; \forall i \in WT$$

There is a space constraint for installing wind turbines. Furthermore, wind turbines can disturb each other if not distant enough. Therefore, it is more interesting to install (if allowed) one big wind turbine instead of many small ones.

- Max x wind turbines in total (e.g., $x = 3$):

$$\sum_{i \in WT} X_i \leq x$$

There is a space constraint for installing wind turbines; one cannot install an infinite number of wind turbines at a client's place.

- Max x cogeneration plants of each type (e.g., $x = 5$):

$$instalCogen_i \leq x \; \forall i \in nbCogen$$

Cogeneration plants can be combined and, thus, their power added, but in terms of space and ease, it is better to favor a small number of big cogeneration plants instead a many small ones.

- Max x cogeneration plants in total (e.g., $x = 8$):

$$\sum_{i \in nbCogen} instalCogen_i \leq x$$

- State of charge of the batteries:

$$state_{Bt+1} = state_{Bt} + charge_t * \eta^{charge} - discharge_t \; \forall t = 1, ..., T-1$$

At each time step, the state of charge of the batteries is defined by the state of charge at the previous time step + the charge at the previous time step - the discharge at the previous time step, the efficiency taken into account.

- The state of charge of the batteries cannot exceed the capacity:

$$state_{Bt} \leq size_B \; \forall t = 1, ..., T$$

- Initial state of charge of the batteries:

$$state_{B0} = s_{B0}$$

- There is a limit of solar panels that can be put per installation:

$$nbSP_{i,Year} \leq Area_i \ \forall i \in SP$$

- Solar panels can be added (but not removed) at the beginning of each year if it does not exceed the limit ($Area_i$):

$$nbSP_{i,y} \geq nbSP_{i,y-1} \ \forall i \in SP \text{ and } \forall y = 2, ..., Year$$

- Extra inverter can be added (but not removed) at the beginning of each year to enlarge the total size of the inverters of the installation:

$$inverter_y \geq nbSP_{y-1} \ \forall y = 2, ..., Year$$

- Formulation of the NPV:

$$NPV = \sum_{y=1}^{Year} \frac{-I_y + R_y - O_y}{(1+\gamma)^y}$$

  The Net Present Value aims to represent the financial value of a project after x years by considering the investments, the operational costs, the revenues, and a discount factor.

- Definition of the CO_2 variable:

$$CO_2 = CO2B * size_B + CO2SP * \sum_{y=1}^{Year} \Big(\sum_{i \in SP} (\sum_{t=1+(y-1)*8760}^{y*8760} ProdSP_{t,i}) * nbSP_{i,y} \Big)$$

$$+ CO2WT * \sum_{i \in WT} (\sum_{t=1}^{T} ProdWT_{t,i}) * X_i + CO2fuel * \sum_{t=1}^{T} (fuel_t)$$

$$+ CO2gas * \sum_{i \in nbCogen(\text{with gas})} \Big(\sum_{t=1}^{T} (gas_{t,i}) * instalCogen_i \Big)$$

$$+ CO2biogas * \sum_{i \in nbCogen(\text{with biogas})} \Big(\sum_{t=1}^{T} (gas_{t,i}) * instalCogen_i \Big)$$

  The CO_2 variable sums all the CO_2 emissions linked to each production or storage solution (batteries, solar panels, wind turbines, generators, and cogeneration plants).

- The gas consumption at each time step for each type of cogeneration plant cannot exceed the sum of its maximum consumption multiplied by the number of cogeneration plants of this type installed:

$$gas_{t,i} \leq ConsoMaxCogen_i * instalCogen_i \ \forall i \in nbCogen \text{ and } \forall t = 1, ..., T$$

  This constraint means the algorithm cannot consider that more gas than the maximum consumption multiplied by the number of cogeneration plants is consumed at a certain time step. This implies that the model cannot assume a production from cogeneration plants that is too high with respect to their production rate (by taking $ConvertGas$ into account).

- The different budgets cannot be exceeded (soft constraints):
  - $BudgetMax \geq I_1 + O_1 - R_1$
  - $ReinvestMax_y \geq I_y + O_y - R_y \ \forall y = 2, ..., Year$

  These constraints are soft because they will be analyzed following the algorithm output. The goal is to maximize NPV or to minimize CO_2. Then, one can verify if the budget constraints are respected. Budgets are more adaptable parameters on the clients' side. They could ask for a bigger loan, for example. The idea is to avoid obtaining an infeasible model due to too restrictive budgets.

- Value of the initial investments:

$$I_1 = \sum_{i \in SP} nbSP_{i,1} * PriceSP_i + \sum_{i \in WT} X_i * PriceWT_i + size_B * Price_B$$

$$+ \sum_{i \in nbCogen} instalCogen_i * PriceCogen_i + inverter_1 * PriceInverter + PriceGen$$

- Value of the reinvestments (linked to additional solar panel and inverter installations):

$$I_y = \sum_{i \in SP} ((nbSP_{i,y} - nbSP_{i,y-1}) * PriceSP_i)$$
$$+ (inverter_y - inverter_{y-1}) * PriceInverter \forall y = 2, ..., Year$$

- Value of the operating costs:

$$O_y = \sum_{i \in nbCogen(\text{with gas})} (\sum_{k=1}^{8760} gas_{8760*(y-1)+k}) * instalCogen_i * PriceGas$$

$$+ \sum_{i \in nbCogen(\text{with biogas})} (\sum_{k=1}^{8760} gas_{8760*(y-1)+k}) * instalCogen_i * PriceBioGas$$

$$+ \sum_{i \in nbCogen} (OpCostCogen_i * instalCogen_i * \frac{8760}{2}) + \sum_{i \in WT} (OpCostWT_i * X_i)$$

$$+ (\sum_{k=1}^{8760} fuel_{8760*(y-1)+k}) * PriceFuel * Penalization \ \forall y = 1, ..., Year$$

  The operating costs gather all the costs linked to the operation of the different production solutions. These are the price of the (bio)gas consumed, the maintenance of the cogeneration plants, and the price of the fuel consumed, which is financially penalized here.

- Value of the revenues during the first year:

$$R_1 = (0.25 * 0.135 + 0.20) * \sum_{i \in WT} (X_i * PriceWT_i)$$

$$+ 0.7 * PriceCV * \sum_{i \in WT} \sum_{t=1}^{8760} (((ProdWT_{t,i})/1000) * X_i)$$

  According to information from Broptimize, for wind turbines, the installations get a deductibility rate of 13,5%, and thus, companies get back 0.25×0.135×price of the installation from taxes. In addition, wind turbines are eligible for UDE help which supports 20% of the price of the installation. Finally, although they no longer exist for solar panels, green certificates still exist for wind turbines. The rate is estimated at 0.7 green certificates per MWh produced with wind turbines. Since the variable $ProdWT_{t,i}$ is in kWh, it has to be divided by 1000 to be converted into MWh.

- Value of the revenues after the first year:

$$R_y = 0.7 * PriceCV * \sum_{i \in WT} \sum_{t=1}^{8760} ((ProdWT_{8760*(y-1)+t,i})/1000) * X_i \ \forall y = 2, ..., Year$$

After the installation year, the left revenues are only those related to the green certificates.

- Positivity constraints (all the variables must be positive):
  - $charge_t, discharge_t, fuel_t, inputSP_t, state_{Bt} \in \mathbf{R}^+ \ \forall t = 1, ..., T$
  - $gas_{t,i} \in \mathbf{R}^+ \ \forall t = 1, ..., T$ and $\forall i \in nbCogen$
  - $I_y, inverter_y, O_y, R_y \in \mathbf{R}^+ \ \forall y = 1, ..., Year$
  - $instalCogen_i \in \mathbf{Z}^+ \ \forall i \in nbCogen$
  - $nbSP_{i,y} \in \mathbf{R}^+ \ \forall i \in SP$ and $\forall y = 1, ..., Year$
  - $size_B \in \mathbf{R}^+$
  - $X_i \in \mathbf{Z}^+ \ \forall i \in WT$ Only an integer number of wind turbines can be installed.

4.7 Adaptation of the formulation for the one-year model

The one-year model only treats data with a one-year horizon. Therefore, the amount of data is significantly reduced. In this model, $Year = 1$ and, thus, $T = 8760$. No reinvestment (new installation of solar panels) is made possible, and the demand does not increase or decrease over the years.

For the high-cost investments to remain attractive, the installation prices of the different production and storage solutions are divided by 15. Indeed, these prices are amortized in the complete model on the project's duration (15 years). However, the prices for 1kWh of gas or 1L of diesel are kept unchanged because this is the consumed quantity that will be adjusted by the algorithm (one generally consumes less in 1 year than in 15 years).

Similarly, the value of the parameters $CO2B$ is also divided by 15 because it concerns the CO_2 emissions of the production of 1kWh of net battery capacity, but these emissions should be amortized over the lifetime of the batteries.

4.8 Adaptation of the formulation for the model with representative days

The model with representative days shrinks even more the amount of data the algorithm must deal with. What days are selected to be representative, and their respective weights are additional parameters specific to each case to add to the model. Since only 12 representative days are considered, the demand and solar panel and wind turbine production data must be adapted. This model only keeps the data relative to the 24 hours of these 12 days.

Similarly to what is done in the one-year model, the installation costs have to be adapted (divided by 15). However, the expression of the operating costs changes compared to the other models. Here, only 12 days are taken into account, but they do not have the same weight. Therefore, the operating costs linked to each day's consumption of (bio)gas and diesel must be multiplied by its weight.

The 12 representative days are very likely to be non-consecutive. They are spread out over the year. Thus, the link between each day in the constraints must be broken. In particular, one cannot consider anymore that the state of charge of the batteries at the end of day d (11:59 PM) is equal to the state of charge of the batteries at the beginning of day $d+1$ (0:01 AM). Therefore, the constraints regarding the batteries' state of charge are specific to each day. An additional variable has been created to model this: SOC_d $\forall d \in$ set of representative days. The constraint

$$state_{Bt+1} = state_{Bt} + charge_t * \eta^{charge} - discharge_t \ \forall t = 1, ..., T-1$$

is kept but holds for the 24 hours of each representative day separately. Two constraints are also added:

$$state_{B_{1+(d-1)*24}} = SOCd \ \forall d \in \text{representative days}$$

$$state_{B_{d*24}} = SOCd \ \forall d \in \text{representative days}$$

These two constraints mean that the batteries' initial and final states of charge for one day must be equal. This is an important assumption that can differ from reality, but this prevents the model from considering that the batteries are heavily charged during a sunny day in summer and that all of this electricity is available for the next representative day, which could be a rainy autumn day. The value of the variable SOC_d is left to the algorithm to be optimized for each representative day.

Chapter 5

Results

This chapter presents the numerous results obtained by applying the three models to the five cases (Hypermarket, Supermarket, Concrete producer, Sawmill, and Potato grower). The graphs show the wind turbine hourly production, solar panel hourly production (in the case the inverter would always convert 100% of it and transmit it to the system), and hourly demand in Kwh of one case depending on the sizing proposed by the algorithm. For these graphs to be legible, their time horizon is limited to 200 hours (± 8 days). The situation of 8 days in June and 8 days in February (November for the Potato grower case) are shown with the hope that they will be representative of what happens in summer and in winter. Of course, there are variations during weeks of two consecutive months, but the goal is to give the reader a general overview to compare the different sizing results more visually. At the end of the chapter, global analyses of the trends that emerge from the five cases are given.

5.1 Hypermarket - 800MWh per year

The Hypermarket case has an electric demand of roughly 800MWh per year. Its demand is very constant over the year, with a small increase during summer, and is generally between 120kWh and 150kWh during the day and between 50kWh and 70kWh during the nights, as shown in Figure A.1.

5.1.1 Results with the complete model

Table 5.1 presents the results obtained for the Hypermarket case with the complete model while optimizing NPV and $CO2$. Figures 5.1 and Figure 5.2 show the evolution of the demand and the wind turbine and solar panel productions during one week of summer and one week in winter, respectively for the results obtained while optimizing NPV and $CO2$.

One should notice that the peak power of solar panels installed, as well as the size of the inverter, are higher when minimizing CO_2. There are also two wind turbines instead of one, and the net battery capacity is significantly more important (factor of 33). This translates into investments almost three times higher in the CO_2 case (but higher revenues with the two wind turbines). This bigger set of production and storage solutions in the CO_2 case decreases the need for (bio)gas but only by 20%.

One can notice that cogeneration plants using gas are chosen in the NPV case and using biogas in the CO_2 case. This will always be the case because biogas is currently more expensive than gas, and cogeneration plants working with biogas are slightly less efficient, so it will never be preferred to gas while focusing on financial aspects.

However, biogas's carbon footprint is four times smaller than gas's. Therefore, if possible, CO_2 will always choose cogeneration plants powered by biogas.

Variables and small description	Values for Max NPV	Values for Min CO_2
X (wind turbines installed)	[0,0,1]	[0, 0, 2]
$nbSP_y$ (solar panels installed)	192.71 kWp (every year, no new installation)	[193.47kWp, 213.68kWp, 227.83kWp, 242.25kWp, 256.51kWp, 271.31kWp, 286.63kWp, 299.0kWp, 299.0kWp, 299.0kWp, 299.0kWp, 299.0kWp, 299.0kWp, 299.0kWp, 299.0kWp]
$inverter_y$ (size of the inverter)	118.83 kWh (every year)	[193.47kWh, 193.47kWh, 209.72kWh, 209.72kWh, 209.72kWh, 220.44kWh, 224.85kWh, 232.22kWh, 232.22kWh, 232.22kWh, 232.22kWh, 232.22kWh, 232.22kWh, 232.22kWh, 232.22kWh]
$size_B$ (net capacity of the batteries)	78.42 kWh	2,620.55 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 3, 0]	[0, 0, 0, 0, 3]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	1,162,519.03 kWh	918,308.02 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	347.92 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	17.00 L	0 L
$\sum_y I_y$ (value of the investments)	2,292,086.49€(mean = 152,805.77 €)	6,203,514.66€(mean = 413,567.64 €)
$\sum_y O_y$ (value of the operational costs)	1,589,156.98€(mean = 105,943.80€)	1,113,451.68 €(mean = 74,230.11 €)
$\sum_y R_y$ (value of the revenues)	1,162,519.03€(mean = 77,501.27 €)	2,325,038.07 €(mean = 155,002.54 €)

Table 5.1: Values of the main variables after solving the sizing algorithm of the complete model on the Hypermarket case for both objective functions

Figure 5.1 gives better insights on the quality of the results prescribed. During summer, solar panel production is close to the consumption during the day but is null during the night, whereas the demand decreases but remains significant. Wind turbine production helps to meet the demand, and the surplus can be stored in the batteries. Wind turbines are necessary in winter because solar panel production is far too small. However, the suggested net capacity of the battery is only 78.42kWh for the NPV case, which is less than one hour's consumption. This is probably because batteries are currently expensive, but more capacity would reduce the need for gas or fuel.

In Figure 5.2, one can see that with the solutions prescribed to minimize CO_2, wind turbine production is sometimes largely superior to the demand. There is a lot of surplus of electricity during summer when solar panel production covers almost the demand. All that surplus must be stored hence the net battery capacity of more than 2MWh. 2MWh corresponds roughly to the consumption of one entire day. Thus, if the battery is full and there is no wind and no sun, the Hypermarket can be powered up for 24 hours without using the cogeneration plants or the generator.

Although the fact of installing two big wind turbines, as suggested in the CO_2 case, is probably an oversizing, this sizing solution allows storing enough electricity to hold one day. In the NPV case, during the nights with low or no wind, the cogeneration plants or the generator are necessary, while it might not be the case in the CO_2 case.

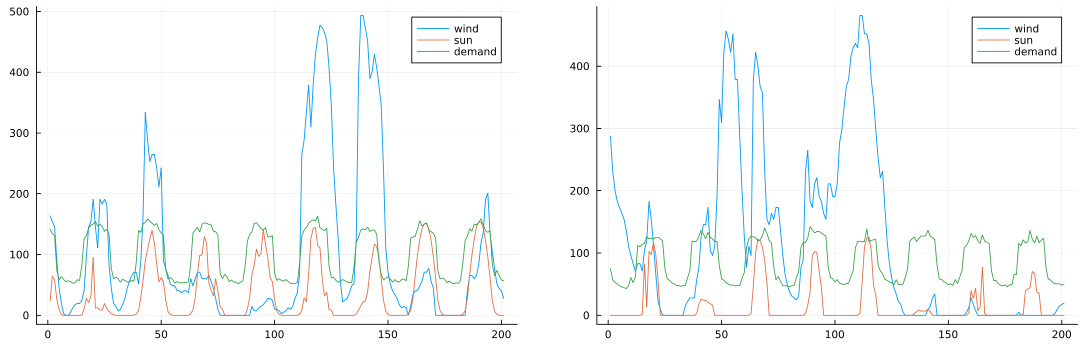

Figure 5.1: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Hypermarket case with the results given by the complete model in summer (left) and in winter (right) while optimizing NPV

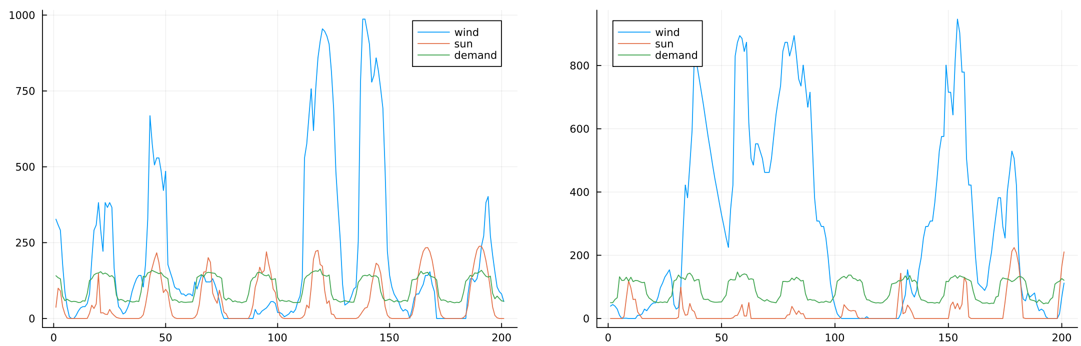

Figure 5.2: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Hypermarket case with the results given by the complete model in summer (left) and in winter (right) while optimizing CO_2

5.1.2 Results with the one-year model

Table 5.2 gathers the results of the one-year model applied to the Hypermarket case for the two objective functions and their combination.

One can notice that the solutions given by NPV and $NPV - CO_2$ are very similar. This will be the case every time for the one-year model and the model with representative days. The main difference is the installation of cogeneration plants with gas for NPV and with biogas for $NPV - CO_2$; gas is more interesting financially, whereas biogas is far more interesting from a carbon footprint point of view. This translates into a value of the variable CO_2 much lower in the $NPV - CO_2$ case.

The suggested peak power of the solar installation is the same for the three objective functions; the maximum. Smaller wind turbine solutions are preferred, but more wind turbines should be installed to minimize the CO_2 emissions. Indeed, the carbon footprint linked to the production of 1kWh of electricity is the smallest compared to the other solutions investigated in this project.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,1,0]	[1, 2, 0]	[0, 1, 0]
$nbSP$ (solar panels installed)	299 kWp	299 kWp	299 kWp
$inverter$ (size of the inverter)	222.35 kWh	289.02 kWh	224.89 kWh
$size_B$ (net capacity of the batteries)	514.14 kWh	4,451.03 kWh	515.83 kWh
$instalCogen$ (cogeneration plants installed)	[0, 3, 0, 0, 0]	[0, 0, 0, 0, 2]	[0, 0, 0, 0, 3]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	369,858.44 kWh	294,384.68 kWh	368,753.94 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	0 L	0 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	0 L	0 L	0 L
I (value of the initial investments)	93,384.25 €	347,285.18 €	97,899.84 €
O (value of the operational costs)	92,445.07 €	62,463.06 €	96,812.13 €
R (value of the revenues)	14,410.57 €	34,248.90 €	14,410.57 €
CO_2 (total CO_2 emissions)	564,348.83 kg	120,576.19 kg	153,419.61 kg

Table 5.2: Values of the main variables after solving the sizing algorithm of the one-year model on the Hypermarket case for both objective functions and their combination

In Figure 5.3, the reader can see that, in the NPV case, coupled with a sufficient battery capacity, solar panels and wind turbines can globally power up the Hypermarket. On the contrary, adding their production does not seem enough to do without cogeneration plants in winter. A higher level of wind turbine production, as in Figure 5.4, allows to power up totally the Hypermarket some days in winter. Thus, even with the maximum peak power of solar panel installation, only one medium wind turbine seems too little. However, this implies higher investment costs and more space required.

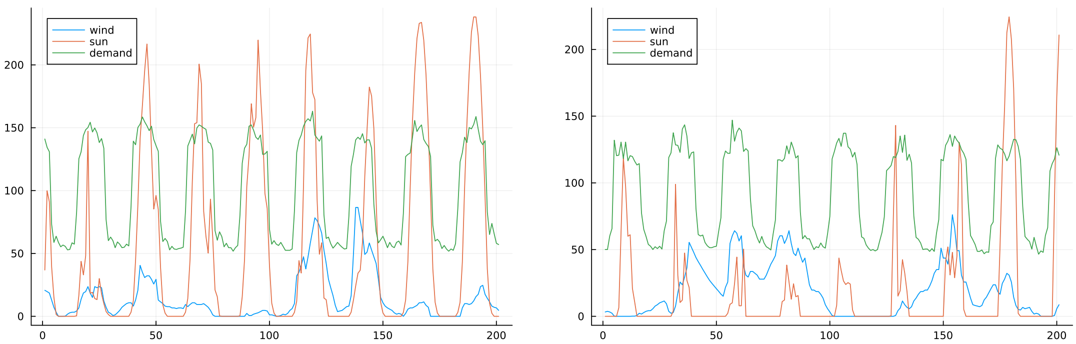

Figure 5.3: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Hypermarket case with the results given by the one-year model in summer (left) and in winter (right) while optimizing NPV

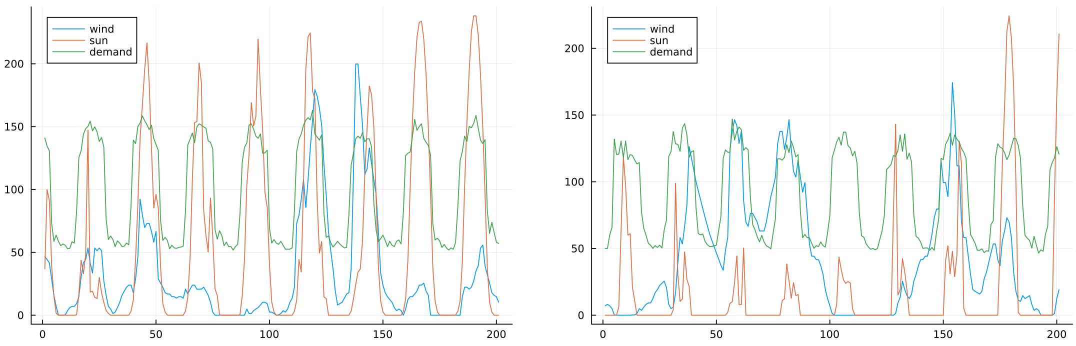

Figure 5.4: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Hypermarket case with the results given by the complete model in summer (left) and in winter (right) while optimizing CO_2

5.1.3 Results with the representative days model

Table 5.3 presents the results obtained for the model with representative days for the two objective functions and their combination. Results while optimizing NPV and $NPV - CO_2$ are again very alike. In both cases, installing the maximum peak power of solar panels and three big wind turbines is suggested when two already seemed too much in the complete case. The battery capacity is very high, sufficient to hold a week. But no cogeneration plant is planned. It looks like the results for the NPV with the model with representative days oversize the production and storage solutions. Nevertheless, one should remember that in an isolated microgrid, backup solutions (cogeneration plants and/or generators) are always needed because anything can happen, for example, a breakdown of the solar panels.

The results for the CO_2 case are similar to those for the CO_2 case in the one-year model. They seem coherent and realistic.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,3]	[0, 2, 0]	[0, 0, 3]
$nbSP$ (solar panels installed)	299 kWp	299 kWp	299 kWp
$inverter$ (size of the inverter)	197.91 kWh	203.43 kWh	197.91 kWh
$size_B$ (net capacity of the batteries)	25,052.94 kWh	1,184.72 kWh	25,052.94kWh
SOC_d (start & end state of charge of the batteries for each representative day d)	[16859kWh, 563kWh, 84 kWh, 2353kWh, 280kWh, 432kWh, 6kWh, 57kWh, 917kWh, 13026kWh, 20816kWh, 23697kWh]	[214kWh, 24kWh, 42kWh, 58kWh, 35kWh, 194kWh, 63kWh, 57kWh, 32kWh, 0kWh, 62kWh, 1089kWh]	[17754kWh, 563kWh, 84 kWh, 2946kWh, 280kWh, 432kWh, 6kWh, 57kWh, 904kWh, 16447kWh, 18982kWh, 23697kWh]
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 0, 0]	[0, 0, 0, 0, 3]	[0, 0, 0, 0, 0]

Table 5.3: Values of the main variables after solving the sizing algorithm of the representative days model on the Hypermarket case for both objective functions and their combination

5.2 Supermarket - 300MWh per year

The Supermarket case has an electric demand of roughly 300MWh per year. Its demand is very constant over the year, similarly to the Hypermarket, with a very small increase during summer, and is generally between 50kWh and 60kWh during the day and between 20Wh and 30kWh during the nights, as shown in Figure A.2.

5.2.1 Results with the complete model

Table 5.4 presents the results of the Supermarket case obtained with the complete model. The observations are alike those made for the Hypermarket case. For the NPV case, fewer solar panels and wind turbines are installed, and the battery capacity is significantly lower. It corresponds only to one to three hours of consumption while, in the CO_2 case, the full battery could last more than a day.

The high investments suggested in the CO_2 case help to reduce the (bio)gas consumption drastically, thus, the operational costs, and increase the revenues with the deductibility and the green certificates linked to wind turbine production.

Variables and small description	Values for Max NPV	Values for Min CO_2
X (wind turbines installed)	[0,1,0]	[0, 3, 0]
$nbSP_y$ (solar panels installed)	103.53 kWp (every year, no new installation)	[111.83kWp, 123.58kWp, 135.41kWp, 138.66kWp, 138.66kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp, 143.0kWp]
$inverter_y$ (size of the inverter)	56.21 kWh (every year)	[89.75kWh, 123.58kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh, 126.66kWh]
$size_B$ (net capacity of the batteries)	78.42 kWh	1,136.47kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 3, 0]	[0, 0, 0, 0, 2]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	3,689,935.80 kWh	582,874.53 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	47.59 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	5.21 L	0 L
$\sum_y I_y$ (value of the investments)	709,066.30€(mean = 47,271.09 €)	2,515,348.29 €(mean = 167,689.87 €)
$\sum_y O_y$ (value of the operational costs)	732,232.51€(mean = 48,815.50 €)	415,340.43 €(mean = 27,689.36 €)
$\sum_y R_y$ (value of the revenues)	211,890.88€(mean = 14,126.06 €)	635,672.65 €(mean = 42,378.18 €)

Table 5.4: Values of the main variables after solving the sizing algorithm of the complete model on the Supermarket case for both objective functions

In Figure 5.5, one can see that in summer, the combined production of the wind turbine and solar panels, coupled with a sufficient battery capacity, could meet the electric demand in most hours. However, in winter, solar panel production is inferior to the demand, and wind turbine production is rarely superior. Thus, the need for cogeneration plants to consume gas and produce electricity as a backup.

In Figure 5.6, this is different. In winter, with the non-negligible battery capacity, the addition of wind turbine and solar panel productions can power up the Supermarket a good part of the time. In summer, the batteries are necessary to store the surplus of electricity during the day for it to be used at night.

In neither case, the installation of one big wind turbine is suggested. In addition to its higher price, it would produce far too much electricity globally compared to the Supermarket's demand level. Since the network is supposed to be islanded, injecting electricity back into the public grid is impossible. Batteries are expensive and have a significant carbon footprint; thus, storing all that electricity can come with a high cost. The wind turbine or the solar panels could be stopped during the periods when their production is superior to the demand and the batteries are full, but this seems to be optimal neither for NPV nor CO_2. It is better to reduce the size of the production solutions.

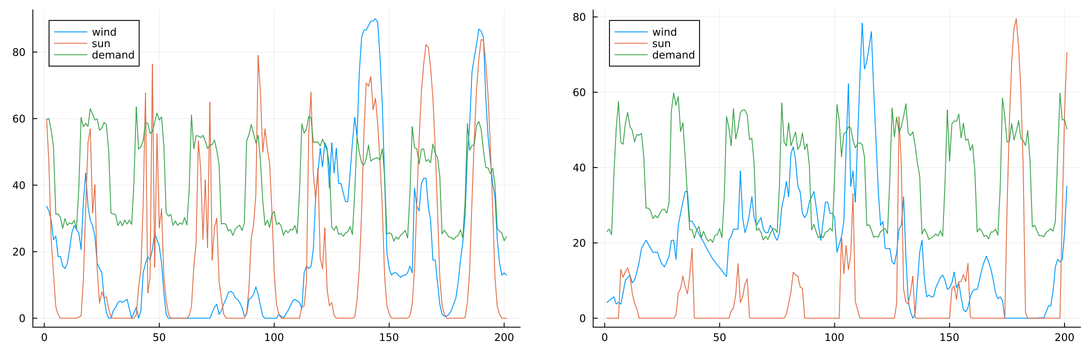

Figure 5.5: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Supermarket case with the results given by the complete model in summer (left) and in winter (right) while optimizing NPV

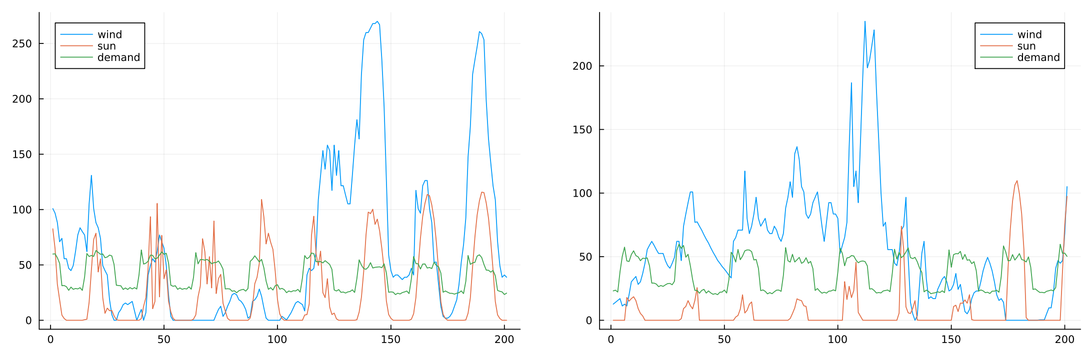

Figure 5.6: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Supermarket case with the results given by the complete model in summer (left) and in winter (right) while optimizing CO_2

5.2.2 Results with the one-year model

Table 5.5 gathers the results of the Supermarket case with the one-year model. In the three cases, the maximum peak power of solar panels is installed. For the NPV and $NPV - CO_2$ cases, the (bio)gas consumption is more or less five times the biogas consumption of the CO_2 case. In the latter, the need for biogas is reduced thanks to installing a medium wind turbine, reducing the project's total CO_2 emissions.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,0]	[0, 1, 0]	[0, 0, 0]
$nbSP$ (solar panels installed)	143 kWp	143 kWp	143 kWp
$inverter$ (size of the inverter)	86.40 kWh	135.69 kWh	120.89 kWh
$size_B$ (net capacity of the batteries)	111.09 kWh	1,563.34 kWh	21.18 kWh
$instalCogen$ (cogeneration plants installed)	[0, 2, 0, 0, 0]	[0, 0, 0, 0, 2]	[0, 0, 0, 0, 2]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	277,054.71 kWh	58,415.92 kWh	302,442.75 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	4.66 L	0 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	2.19 L	0 L	0 L
I (value of the initial investments)	23,343.02 €	133,488.97 €	21,236.81 €
O (value of the operational costs)	46,110.68 €	22,427.43 €	52,653.15 €
R (value of the revenues)	0 €	14,542.75 €	0 €
CO_2 (total CO_2 emissions)	279,779.52 kg	34,324.99 kg	80,240.65 kg

Table 5.5: Values of the main variables after solving the sizing algorithm of the one-year model on the Supermarket case for both objective functions and their combination

In Figure 5.7 and Figure 5.8, one can see that, in winter, solar panel production is really not sufficient. With only one medium wind turbine and the maximum peak power of solar panels, the need for gas is reduced, and the potential oversizing looks limited. The medium wind turbine produces around 180MWh per year. Solar panels can complete the electricity input to supply the 300MWh of annual consumption with a limited (bio)gas consumption. Sufficient battery capacity is also needed to ensure renewable electricity consumption at night when solar panels do not produce at all.

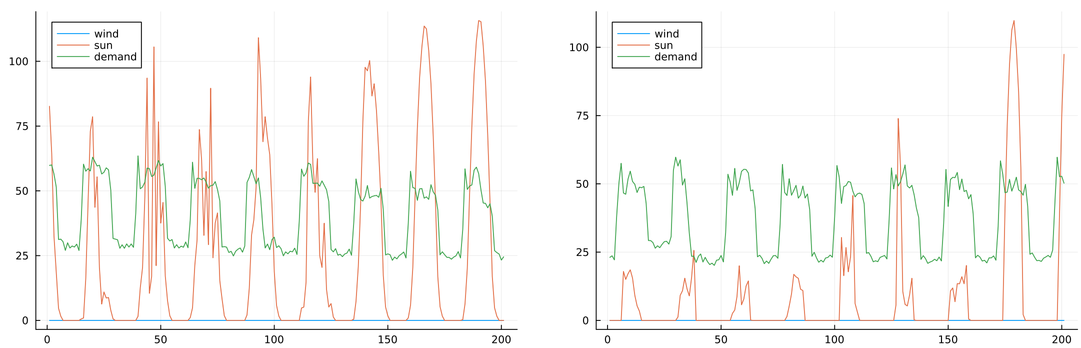

Figure 5.7: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Supermarket case with the results given by the one-year model in summer (left) and in winter (right) while optimizing NPV

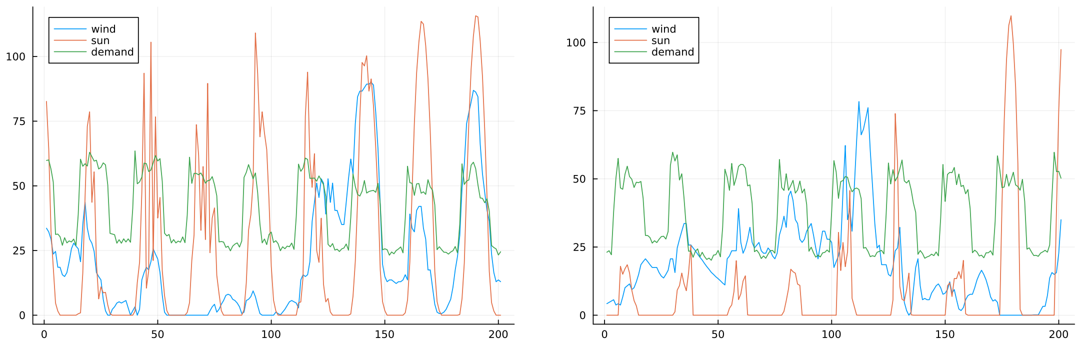

Figure 5.8: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Supermarket case with the results given by the one-year model in summer (left) and in winter (right) while optimizing $CO2$

5.2.3 Results with the representative days model

In Table 5.6, the reader can find the results of the model with representative days applied to the Supermarket case. The sizing proposed while optimizing NPV or $NPV - CO_2$ is surprising. The big wind turbine's production is too important compared to the Supermarket's consumption. There is an oversizing with a very big battery capacity and large production solutions. It seems that the algorithm wants to avoid using (bio)gas. This sizing solution would be very complicated and unreasonable to implement.

The solution proposed while minimizing CO_2 involves no solar panels, only wind turbines (and biogas). This is probably because wind turbines' carbon footprint is inferior to solar panels' carbon footprint (14g per kWh produced instead of 45g). Nonetheless, none of the sizing solutions for the Supermarket case proposed by the representative days model are convincing.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,1]	[1, 2, 0]	[0, 0, 1]
$nbSP$ (solar panels installed)	143 kWp	0 kWp	143 kWp
$inverter$ (size of the inverter)	86.53 kWh	0 kWh	86.53 kWh
$size_B$ (net capacity of the batteries)	6,780.67 kWh	1,843.78 kWh	6,780.67kWh
SOC_d (start & end state of charge of the batteries for each representative day d)	[20kWh, 2902kWh, 1910kWh, 158kWh, 3274kWh, 86kWh, 3063kWh, 55kWh, 3165kWh, 21kWh, 71kWh, 6380kWh]	[20kWh, 353kWh, 123kWh, 25kWh, 420kWh, 13kWh, 437kWh, 2kWh, 408kWh, 21kWh, 11kWh, 1737kWh]	[20kWh, 2770kWh, 2187kWh, 158kWh, 3416kWh, 86kWh, 4297kWh, 55kWh, 3149kWh, 21kWh, 71kWh, 6380kWh]
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 0, 0]	[0, 0, 0, 0, 2]	[0, 0, 0, 0, 0]

Table 5.6: Values of the main variables after solving the sizing algorithm of the representative days model on the Supermarket case for both objective functions and their combination

5.3 Concrete producer - 70MWh per year

The Concrete producer case has an electric demand of roughly 70MWh per year. Its demand, shown in Figure A.3, varies greatly depending on the day (weekday or weekend). Unlike the Hypermarket and the Supermarket case, the electric demand at night is almost null. During the day, the hourly demand rarely exceeds 55kWh.

5.3.1 Results for the complete model

In Table 5.7, the reader can see the algorithm's results for the complete model. For both objective functions, the peak power of the solar panels prescribed is far from the maximum that can be installed. While optimizing the NPV, the renewable solutions are very limited; no wind turbine, few solar panels, and little battery capacity. The powering up relies almost exclusively on gas and cogeneration plants. Installing a medium wind turbine and increasing the battery capacity while minimizing CO_2 reduces by a factor of 6 the need for (bio)gas at the cost of high investments. However, the medium wind turbine might be too big for the Concrete producer case because its yearly production is superior to the yearly consumption unless the demand for electricity rises sharply over the next few years.

Variables and small description	Values for Max NPV	Values for Min CO_2
X (wind turbines installed)	[0,0,0]	[0, 1, 0]
$nbSP_y$ (solar panels installed)	14.78 kWp (every year, no new installation)	[10.12kWp, 12.01kWp, 12.20kWp, 13.41kWp, 18.03kWp, 21.25kWp, 24.57kWp, 27.04kWp, 29.11kWp, 31.50kWp, 33.01kWp, 34.27kWp, 35.81kWp, 41.51kWp, 42.72kWp]
$inverter_y$ (size of the inverter)	10.01 kWh (every year)	[10.12kWh, 10.90kWh, 11.02kWh, 13.41kWh, 16.12kWh, 18.90kWh, 21.75kWh, 23.82kWh, 25.51kWh, 27.46kWh, 28.64kWh, 30.79kWh, 30.79kWh, 35.51kWh, 36.33kWh]
$size_B$ (net capacity of the batteries)	13.19 kWh	422.48 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 2, 0, 0]	[0, 0, 0, 0, 1]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	1,568,935.46 kWh	256,467.52 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	90.27 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	4.12 L	0 L
$\sum_y I_y$ (value of the investments)	162,884.61€(mean = 10,858.97 €)	914,209.01 €(mean = 60,947.27 €)
$\sum_y O_y$ (value of the operational costs)	376,999.60 €(mean = 25,133.31 €)	154,821.73 €(mean = 10,321.45 €)
$\sum_y R_y$ (value of the revenues)	0€(mean = 0 €)	219,827.17 €(mean = 14,655.14 €)

Table 5.7: Values of the main variables after solving the sizing algorithm of the complete model on the Concrete producer case for both objective functions

In Figure 5.9, one can see that the solar panel production alone cannot power up the Concrete producer if only 15kWp are installed neither in summer nor in winter. During weekends, the solar panels can charge the batteries, but their capacity is very low in the NPV case.

The situation in Figure 5.10 is different. Wind turbine production can power up the Concrete producer most of the time. Coupled with solar panels and a battery capacity that can supply the system alone for about two days, biogas consumption is limited compared to the NPV case. Although the choice of a small wind turbine instead of a medium one might have been better, the solution suggested while minimizing CO_2 seems better than the one while maximizing NPV.

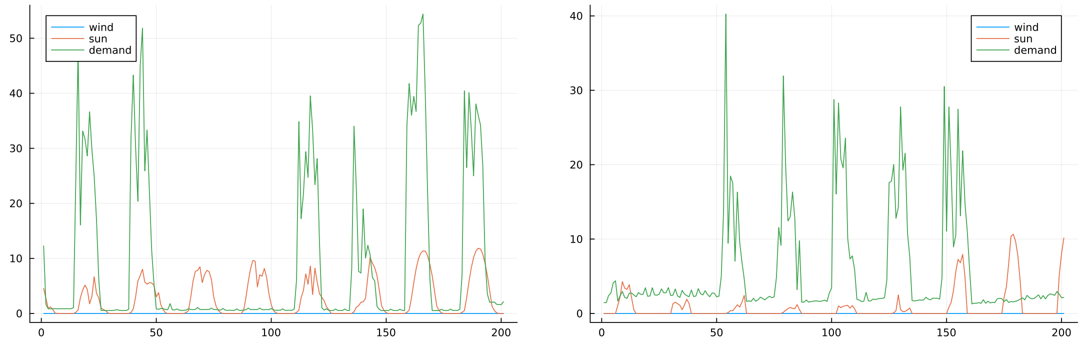

Figure 5.9: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Concrete producer case with the results given by the complete model in summer (left) and in winter (right) while optimizing NPV

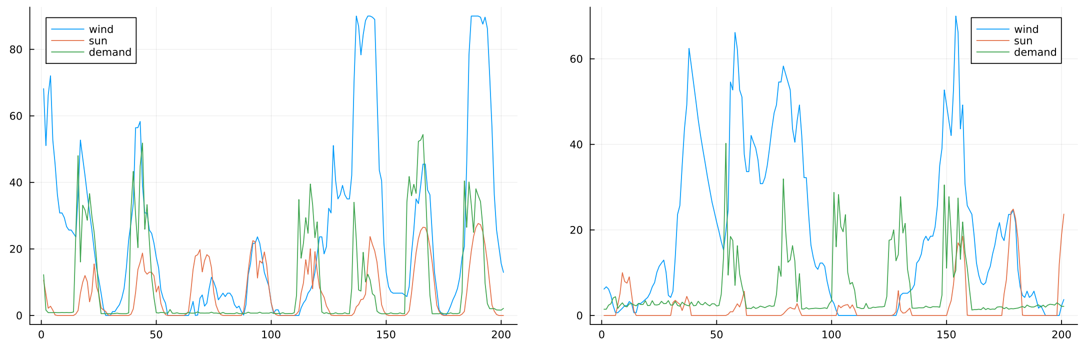

Figure 5.10: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Concrete producer case with the results given by the complete model in summer (left) and in winter (right) while optimizing $CO2$

5.3.2 Results for the one-year model

Table 5.8 presents the results obtained with the one-year model for both objective functions and their combination. Similarly to the results of the complete model, no wind turbine is installed in the NPV case, but there is one in the CO_2 case. The difference is that the chosen wind is the small one, not the medium. In addition, the peak power of the solar panel installation is higher than with the complete model, especially in the NPV case. The need for (bio)gas is proportionally reduced in the one-year model compared to the complete one. With a wind turbine and less (bio)gas consumption, the CO_2 emissions linked to the results while minimizing CO_2 are four times smaller than those linked to the results while maximizing NPV.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,0]	[1, 0, 0]	[0, 0, 0]
$nbSP$ (solar panels installed)	69.74 kWp	40.65 kWp	91.02 kWp
$inverter$ (size of the inverter)	40.42 kWh	37.75 kWh	48.03 kWh
$size_B$ (net capacity of the batteries)	49.93 kWh	1,070.37 kWh	54.76 kWh
$instalCogen$ (cogeneration plants installed)	[0, 2, 0, 0, 0]	[0, 0, 0, 0, 1]	[0, 2, 0, 0, 0]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	45,693.34 kWh	11,994.40 kWh	38,673.85 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	12.81 L	0 L	8.99 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	4.88 L	0 L	4.88 L
I (value of the initial investments)	15,636.18 €	82,220.61 €	17,034.67 €
O (value of the operational costs)	13,964.67 €	8,964.21 €	12,867.13 €
R (value of the revenues)	0 €	5,573.93 €	0 €
CO_2 (total CO_2 emissions)	48,444.87 kg	11,235.26 kg	42,595.25 kg

Table 5.8: Values of the main variables after solving the sizing algorithm of the one-year model on the Concrete producer case for both objective functions and their combination

In Figure 5.11, one can notice that with 70kWp of solar panels and a sufficient battery capacity, the Concrete producer could almost be powered up only with solar panels. Since the demand during weekends is minimal, solar panels could charge the batteries to make a stock in case of need during weekdays. However, this is not the case in winter; solar panel production is insufficient. But the battery capacity proposed for the NPV case does not allow to stock enough electricity to power the system up in case of cloudy days with low solar panel production.

In addition, during the summer holidays, the company is closed for two weeks. The demand is almost null during this period, but the production of solar panels should be high. Therefore, the company would have to shut down the solar panels during its closure because the battery could not stock all the electricity produced.

In Figure 5.12, the reader can see that the combination of the solar panel and small wind turbine productions seems generally sufficient to power up the system, especially in summer. The need for biogas is probably mostly limited to some days in winter. The battery capacity suggested is high and can store electricity for several days. Nevertheless, this implies higher investment costs.

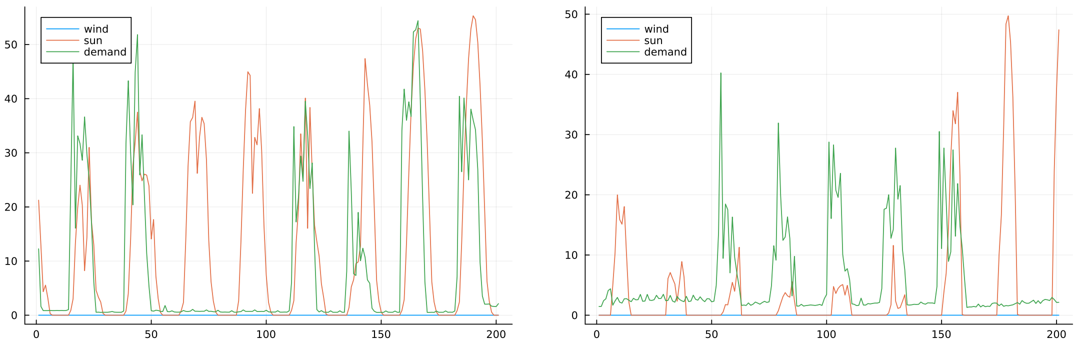

Figure 5.11: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Concrete producer case with the results given by the one-year model in summer (left) and in winter (right) while optimizing NPV

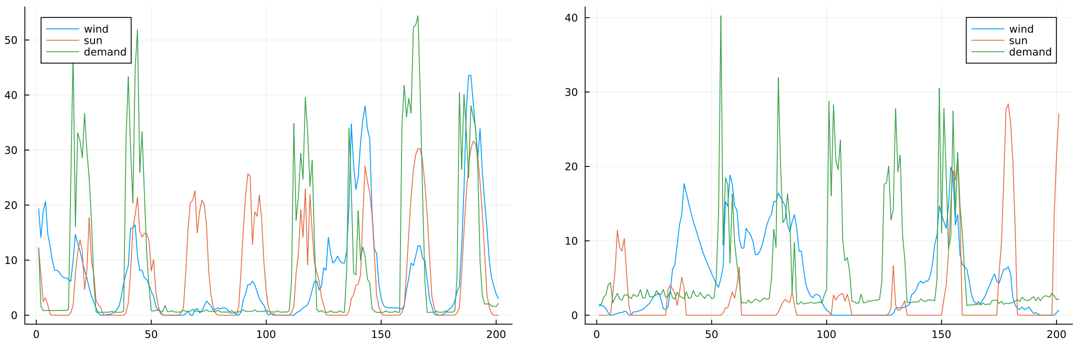

Figure 5.12: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Concrete producer case with the results given by the one-year model in summer (left) and in winter (right) while optimizing $CO2$

5.3.3 Results with the representative days model

Table 5.9 presents the results obtained with the representative days model for both objective functions and their combination in the Concrete producer case. The analysis is close to those of the two previous cases with the same model. With NPV and $NPV - CO_2$, there is a significant oversizing. As stated in the analysis of the complete model, the medium wind turbine produces too much compared to the Concrete producer demand, and the surplus cannot be injected into the public grid. The maximum peak power of solar panel installation is added to the medium wind turbine to avoid using (bio)gas.

Installing one medium wind turbine in the Concrete producer case could be justifiable if a very sharp increase in demand was expected. However, the model with representative days takes only into account the data from representative days of one year.

The solution proposed in the CO_2 case seems more reasonable but relies only on the wind (and biogas), not the sun. The battery capacity could store enough electricity to power up the system for a coupled of days. Nevertheless, it seems safer to diversify one's electricity source of production.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,1,0]	[2,0,0]	[0, 1, 0]
$nbSP$ (solar panels installed)	129 kWp	0 kWp	129 kWp
$inverter$ (size of the inverter)	28.28 kWh	0 kWh	28.28 kWh
$size_B$ (net capacity of the batteries)	985.92 kWh	560.06 kWh	985.92kWh
SOC_d (start & end state of charge of the batteries for each representative day d)	[693kWh, 167kWh, 223kWh, 32kWh, 19kWh, 497kWh, 181kWh, 296kWh, 484kWh, 806kWh, 948kWh, 0kWh]	[355kWh, 14kWh, 141kWh, 50kWh, 1kWh, 460kWh, 92kWh, 70kWh, 271kWh, 445kWh, 539kWh, 0kWh]	[757kWh, 167kWh, 223kWh, 32kWh, 19kWh, 501kWh, 181kWh, 296kWh, 483kWh, 819kWh, 948kWh, 0kWh]
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 0, 0]	[0, 0, 0, 0, 1]	[0, 0, 0, 0, 0]

Table 5.9: Values of the main variables after solving the sizing algorithm of the representative days model on the Concrete producer case for both objective functions and their combination

5.4 Sawmill - 3000MWh per year

The Sawmill case has an electric demand of about 3000MWh per year. This is the case with the highest level of demand considered in this project. Its demand structure is similar to the Concrete producer case, although the consumption levels differ. The demand varies greatly depending on the day (weekday or weekend). During working hours, the hourly demand is around 1000kWh. The rest of the time, the hourly demand is lower and comes close to 100-150kWh, as shown in Figure A.4.

5.4.1 Results for the complete model

The results obtained with the complete model for both objective functions can be found in Table 5.10. The solutions prescribed while optimizing NPV or CO_2 are very similar. Both suggest installing the maximum peak power of solar panels and three big wind turbines. In both cases, this translates into high investment costs (more than 24 billion €). The battery capacity (more than 20MWh) is sufficient to store electricity to power up the Sawmill for two days (if full) in case of days without sun or wind.

The main difference lies in the use of gas in the NPV case and of biogas in the CO_2 case, for reasons already raised earlier. This is the first case of such a strong need for fuel, especially while minimizing the CO_2 emissions. An additional cogeneration plant, if there is room for it, could help to reduce this fuel consumption in favor of (bio)gas.

Variables and small description	Values for Max NPV	Values for Min CO_2
X (wind turbines installed)	[0,0,3]	[0, 0, 3]
$nbSP_y$ (solar panels installed)	1800 kWp (every year, no new installation)	1800 kWp (every year, no new installation)
$inverter_y$ (size of the inverter)	1161.94 (every year)	1622.82kWh (every year)
$size_B$ (net capacity of the batteries)	20,913.26 kWh	21,107.27 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 3, 0]	[0, 0, 0, 0, 3]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	5,645,631.27 kWh	4,873,319.23 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	616,635.6 L	832,882.9 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	424.3L	443.8 L
$\sum_y I_y$ (value of the investments)	24,498,082.33€(mean = 1,633,205.49 €)	24,728,423.51 €(mean = 1,648,561.57 €)
$\sum_y O_y$ (value of the operational costs)	27,116,614.11 €(mean = 1,807,774.27 €)	35,604,319.78 €(mean = 2,373,621.32 €)
$\sum_y R_y$ (value of the revenues)	3,140,163.29€(mean = 209,344.22 €)	3,140,163.29 €(mean = 209,344.22 €)

Table 5.10: Values of the main variables after solving the sizing algorithm of the complete model on the Sawmill case for both objective functions

In Figure 5.13 are represented the wind turbine and solar panel production and the demand during one week in summer and one week in winter with the solutions prescribed by the algorithm. These graphs hold for both objective functions because, in both cases, there are three wind turbines and a peak power of 1800kWp of solar panels.

In summer, solar panel production is generally sufficient, but the demand at night is not null. Therefore, some electricity must be stored in the batteries during the day thanks to the surplus from the combined production of wind turbines and solar panels to avoid using (bio)gas or fuel. In winter, solar panel production is very inferior to electric consumption. Wind turbines can partially supply the Sawmill but are not enough daily, especially if the wind is not very strong.

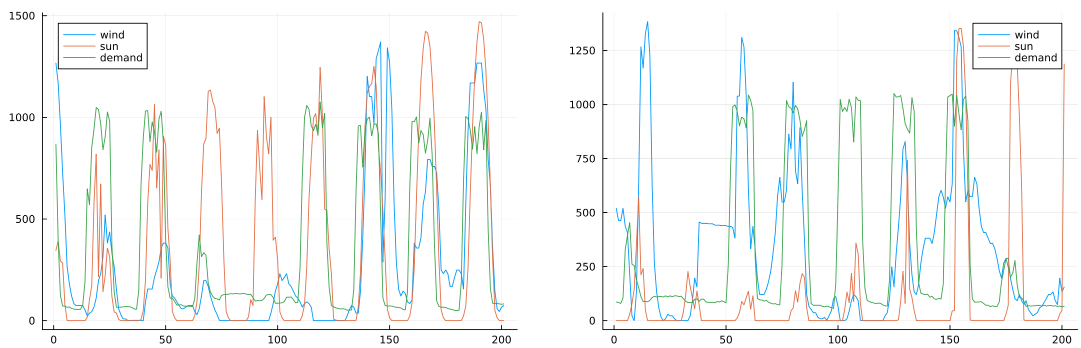

Figure 5.13: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Sawmill case with the results given by the complete model in summer (left) and in winter (right) for both objective functions

5.4.2 Results for the one-year model

Table 5.11 presents the results of the Sawmill case obtained with the one-year model for both objective functions and their combination. What is proposed in the NPV case is not really convincing. The peak power of the solar panel installation is maximum, as in the CO_2 case, but only one medium wind turbine is installed, and the battery capacity is very low. Given the consumption levels in the Sawmill case, the medium can help slightly reduce the need for (bio)gas or fuel, but the big one seems more adapted. However, seven cogeneration plants are installed here instead of three in the complete model.

Although the need for gas is proportionally higher, no fuel is used in the one-year model, which is likely to be positive in terms of CO_2 emissions. Nonetheless, one should remember that in the complete model, an increase of 2% per year in demand is planned. Therefore, the solution proposed in the CO_2 case, with two big wind turbines instead of three in the complete model and a battery capacity that can cover more than a day's consumption, looks interesting if the company foresees no significant increase or a decrease in electric consumption.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,1,0]	[0, 0, 2]	[0, 1, 0]
$nbSP$ (solar panels installed)	1800 kWp	1800 kWp	1800 kWp
$inverter$ (size of the inverter)	1020.2 kWh	1727.96 kWh	1025.07 kWh
$size_B$ (net capacity of the batteries)	263.01 kWh	22,841.40 kWh	263.01 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 7, 0]	[0, 0, 0, 0, 7]	[0, 0, 0, 0, 8]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	766,161.55 kWh	160,473.89 kWh	670,288.65 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	0 L	0 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	0 L	0 L	0 L
I (value of the initial investments)	245,762.74 €	1,665,354.12 €	250,744.36 €
O (value of the operational costs)	415,291.36 €	160,504.41 €	420,358.44 €
R (value of the revenues)	12,977.69 €	144,381.38 €	12,977.69 €
CO_2 (total CO_2 emissions)	2,716,743.71 kg	399,645.27 kg	732,286.63 kg

Table 5.11: Values of the main variables after solving the sizing algorithm of the one-year model on the Sawmill case for both objective functions and their combination

In Figure 5.14, the reader can see that the production of one medium wind turbine (in blue) in both summer and winter is very low compared to the hourly demand (in green). In summer, solar panels can supply most of the time the Sawmill during working hours and charge the batteries during the weekend to ensure night consumption or a drop in production if there are some cloudy or rainy hours. However, solar production is totally insufficient in winter, and there is a strong need for backup solar as cogeneration plants.

Figure 5.15 is similar to Figure 5.13; only the blue line has been tightened by 33%. In summer, the coupled production of wind turbines and solar panels, with a significant storage capacity, seems sufficient to ensure day and night consumption. The wind turbines produce more in winter than in summer, but sometimes there is still a need for some electric production thanks to the cogeneration plants.

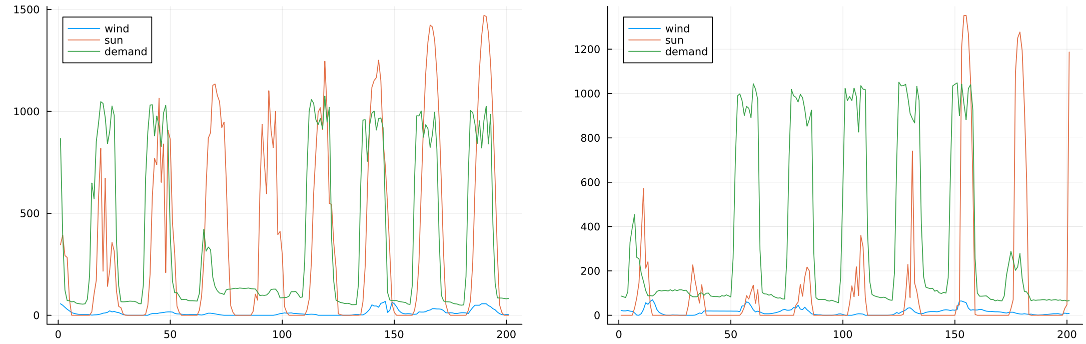

Figure 5.14: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Sawmill case with the results given by the one-year model in summer (left) and in winter (right) while optimizing NPV

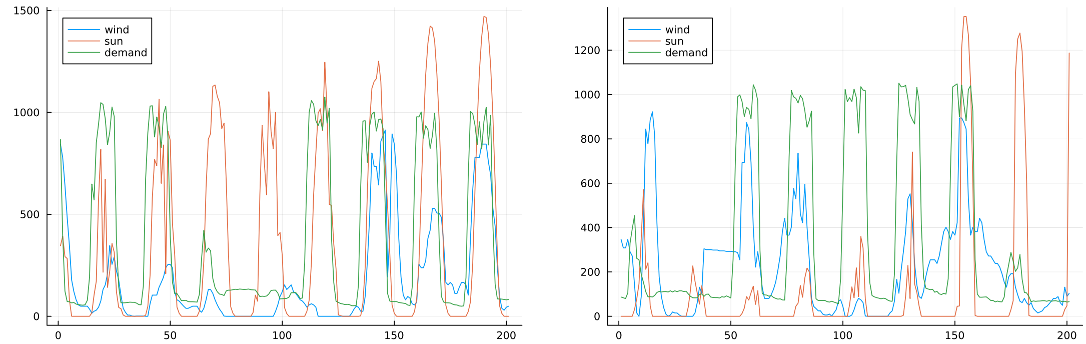

Figure 5.15: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Sawmill case with the results given by the one-year model in summer (left) and in winter (right) while optimizing $CO2$

5.4.3 Results with the representative days model

Table 5.12 gathers the results obtained with the representative days in the Sawmill case. For the NPV and $NPV - CO_2$ cases, three big wind turbines and 1800kWp of solar panels are installed as in the complete case. However, the battery capacity is significantly increased. Still, no cogeneration plant is installed, which means that in case of no wind, no sun, and empty batteries, this is inevitably fuel that will be consumed.

As for the Concrete producer case, when the model with representative days minimizes the CO_2 emissions, it suggests not installing solar panels, only wind turbines, batteries, and cogeneration plants supplied with biogas. Nevertheless, it would be better to rely on both sun and wind to produce renewable electricity because in the case of failure of the wind turbines or if there is no wind for too long, the system will have to turn to biogas or fuel.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,3]	[0,0,3]	[0, 0, 3]
$nbSP$ (solar panels installed)	1800 kWp	0 kWp	1800 kWp
$inverter$ (size of the inverter)	995.44 kWh	0 kWh	995.44 kWh
$size_B$ (net capacity of the batteries)	19,150.33 kWh	19,146.05 kWh	19,150.33kWh
SOC_d (start & end state of charge of the batteries for each representative day d)	[17777kWh, 2821kWh, 6038kWh, 16kWh, 7716kWh, 28kWh, 22kWh, 3kWh, 424kWh, 270kWh, 66kWh, 130kWh]	[17773kWh, 2794kWh, 6622kWh, 2050kWh, 10450kWh, 2297kWh, 2208kWh, 1564kWh, 297kWh, 2132kWh, 1574kWh, 47kWh]	[17777kWh, 2903kWh, 6038kWh, 16kWh, 7716kWh, 28kWh, 22kWh, 3kWh, 424kWh, 270kWh, 66kWh, 130kWh]
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 0, 0]	[0, 0, 0, 0, 5]	[0, 0, 0, 0, 0]

Table 5.12: Values of the main variables after solving the sizing algorithm of the representative days model on the Sawmill case for both objective functions and their combination

5.5 Potato grower - 25MWh per year

The Potato grower case has an electric demand of roughly 25MWh per year. This is the case with the lowest level of demand considered in this project but also the most atypical. As shown in Figure A.5, the demand is almost null during several months in the summer before skyrocketing in October when the potatoes are harvested and stored in specific conditions. Then, the demand diminishes over the months. In October, the hourly demand can reach 25kWh but is between 0kWh and 10kWh most of the time.

5.5.1 Results for the complete model

In Table 5.13, the reader can find the results obtained with the complete model of the Potato grower case. For both objective functions, no solar panel is installed (thus, no inverter). It seems consistent with the fact that solar panels produce the most in summer when the Potato grower's demand is almost null. With no possibility of injecting electricity into the public grid, the battery capacity would have to be huge to stock the solar panel production. Wind turbines produce more during autumn and winter, corresponding to when the Potato grower's demand is the highest. Installing one wind turbine seems, therefore, to be a reasonable choice.

In the NPV case, the big wind turbine is suggested. However, it would produce far too much compared to the consumption, even during the peaks. This solution is interesting from a financial point of view because of the green certificates granted for wind turbine production and the deductibility of the investment. But, the model does not use the electricity produced in summer and does not stock it. It virtually consumes it by using the charge and discharge efficiencies of the batteries that are $<$ 100% because the system is isolated. In practice, this solution is not very good.

In the CO_2 case, the medium wind turbine is chosen. Revenues are smaller, but so does the investments. In addition, the need for biogas is reduced, and no fuel is used in this configuration. The battery capacity is higher than in the NPV case, sufficient to power up the system for at least 3 hours. Still, it cannot store the electricity produced by the wind turbine in summer when the consumption is at its lowest levels. Nonetheless, the solution proposed in the CO_2 case is better than the one proposed while maximizing NPV.

Variables and small description	Values for Max NPV	Values for Min CO_2
X (wind turbines installed)	[0,0,1]	[0, 1, 0]
$nbSP_y$ (solar panels installed)	0 kWp (every year, no new installation)	0 kWp (every year, no new installation)
$inverter_y$ (size of the inverter)	0kWh (every year)	0kWh (every year)
$size_B$ (net capacity of the batteries)	1.31 kWh	66.55 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 1, 0]	[0, 0, 0, 0, 2]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	139,789.0 kWh	116,298.97 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	105.9 L	0 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	2.19 L	0 L
$\sum_y I_y$ (value of the investments)	1,850,917.24€(mean = 123,394.48 €)	629,111.61 €(mean = 41,940.77 €)
$\sum_y O_y$ (value of the operational costs)	435,890.60€(mean = 29,059.37 €)	230,019.86 €(mean = 15,334.66 €)
$\sum_y R_y$ (value of the revenues)	1,229,932.41€(mean = 81,995.49€)	216,857.27 €(mean = 14,457.15 €)

Table 5.13: Values of the main variables after solving the sizing algorithm of the complete model on the Potato grower case for both objective functions

In Figure 5.16, one can see how high the big wind turbine production levels are compared to the consumption levels. In addition, the tiny battery capacity cannot store enough electricity coming from the wind turbines to power up the system when there is no wind for one hour, so gas and fuel still have to be used.

In Figure 5.17, the medium wind turbine production can be compared to the demand levels in winter and summer. One should notice that the graph on the right is realized with the production and demand data for one week in November (when the demand is high) and not in February, unlike the four previous cases.

Given the battery capacity in the CO_2 case, the wind turbine would have to be stopped most of the time in summer (as soon as the batteries are full). However, wind turbine production can supply much of the electricity needed in winter, reducing the need for gas and fuel.

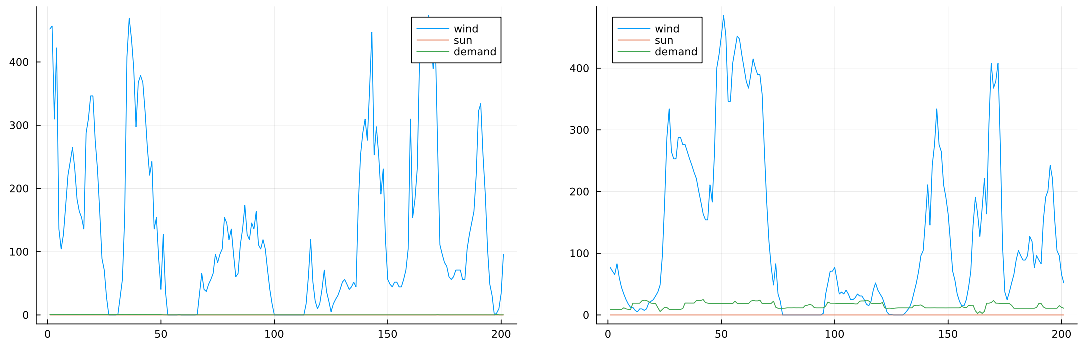

Figure 5.16: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Potato grower case with the results given by the complete model in summer (left) and in winter (right) while optimizing NPV

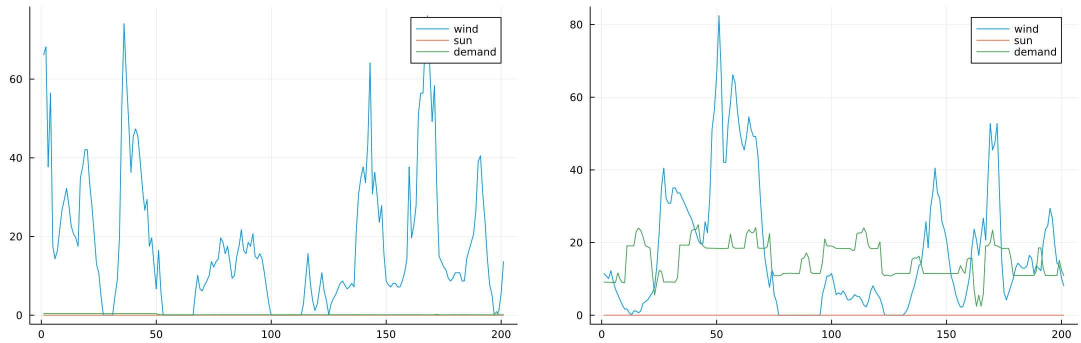

Figure 5.17: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Potato grower case with the results given by the complete model in summer (left) and in winter (right) while optimizing $CO2$

5.5.2 Results for the one-year model

Table 5.14 presents the results obtained with the one-year model. They are surprising because a wind turbine is suggested in none of the cases. Instead, a few solar panels are installed coupled with a small battery capacity. In the NPV and $NPV - CO_2$ cases, almost all the demand is assured by gas. The bigger installation of solar panels in the CO_2 cases divides by 3 the need for (bio)gas, but this is still proportionally high compared to the consumption in the complete case.

Therefore, installing a wind turbine is more likely to be tailored to the atypical demand of the Potato grower than solar panels. Still, a bigger battery capacity could reduce the (bio)gas consumption. Still, one should remember that batteries have a significant carbon footprint, mainly due to the energy required to extract the raw materials and produce them.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,0,0]	[0, 0, 0]	[0, 0, 0]
$nbSP$ (solar panels installed)	5.84 kWp	34.50 kWp	13.43 kWp
$inverter$ (size of the inverter)	3.77 kWh	30.40 kWh	8.19 kWh
$size_B$ (net capacity of the batteries)	11.79 kWh	54.61 kWh	13.16 kWh
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 1, 0]	[0, 0, 0, 0, 2]	[0, 0, 0, 1, 0]
$\sum_{i \in nbCogen} \sum_t gas_{it}$ (sum of the kWh of gas consumed)	69,417.65 kWh	24,986.61 kWh	64,272.88 kWh
$\sum_t fuel_t$ (sum of the liters of fuel consumed)	3.41 L	0 L	1.61 L
$max\ fuel_t$ (maximum number of liters of fuel consumed in one hour)	0.96 L	0 L	0.86 L
I (value of the initial investments)	6,529.75 €	14,646.13 €	7,026.99 €
O (value of the operational costs)	10,086.13 €	13,747.33 €	9,672.14 €
R (value of the revenues)	0 €	0 €	
CO_2 (total CO_2 emissions)	34,404.24 kg	8,146.81 kg	32,281.05 kg

Table 5.14: Values of the main variables after solving the sizing algorithm of the one-year model on the Potato grower case for both objective functions and their combination

In Figure 5.18 and Figure 5.19, the reader can graphically see that solar panel production is high in summer but totally useless (no demand) and insufficient during autumn and winter to supply the system in electricity. The solar panel installation would have to be disconnected or stopped during summer because the electricity produced would not be consumed nor used.

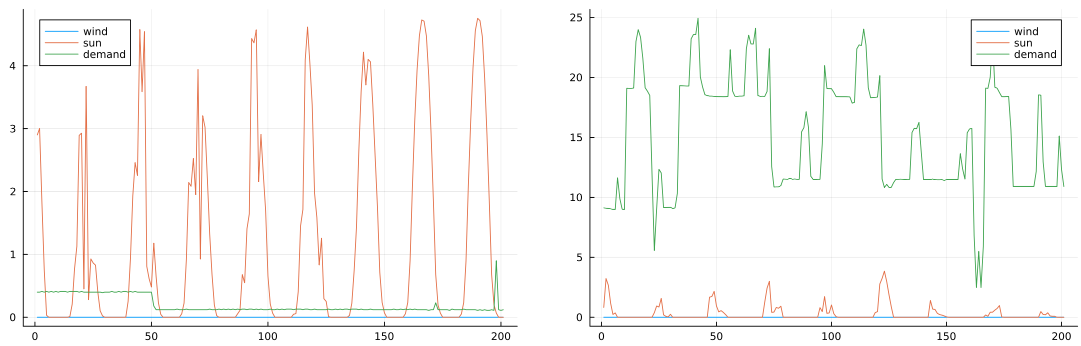

Figure 5.18: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Potato grower case with the results given by the one-year model in summer (left) and in winter (right) while optimizing NPV

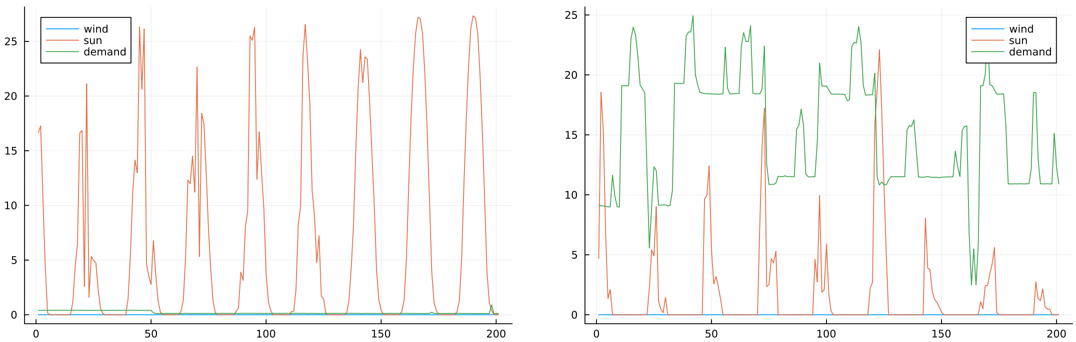

Figure 5.19: Wind turbine production (blue), solar panel production (orange), and demand (green) for the Potato grower case with the results given by the one-year model in summer (left) and in winter (right) while optimizing $CO2$

5.5.3 Results with the representative days model

Table 5.15 gathers the results of the model with representative days applied to the Potato grower case. With the three objective functions, a wind turbine is suggested, coupled with solar panels while optimizing NPV and $NPV - CO_2$. The capacity of the batteries for these two objective functions is high and can store enough electricity for several autumn days. This could theoretically make it possible to power up the system without cogeneration plants or gas.

The sizing solution proposed while minimizing CO_2 includes one cogeneration plant as a backup. It is similar to the solution for the complete model in the CO_2 case; no solar panels are installed, just one wind turbine (but the small one instead of the medium one). These two solutions seem to be the most convincing for the Potato grower case. Only proposing a wind turbine and batteries might be surprising, but solar panels are not well suited for this very atypical demand structure.

Variables and small description	Values for Max NPV	Values for Min CO_2	Values for Max $NPV - CO_2$
X (wind turbines installed)	[0,1,0]	[1,0,0]	[0, 1, 0]
$nbSP$ (solar panels installed)	94.83 kWp	0 kWp	94.83 kWp
$inverter$ (size of the inverter)	33.84 kWh	0 kWh	33.84 kWh
$size_B$ (net capacity of the batteries)	1,282.49 kWh	381.16 kWh	1,282.49kWh
SOC_d (start & end state of charge of the batteries for each representative day d)	[515kWh, 1196kWh, 583kWh, 30kWh, 42kWh, 45kWh, 125kWh, 198kWh, 28kWh, 658kWh, 697kWh, 625kWh]	[232kWh, 353kWh, 175kWh, 3kWh, 7kWh, 7kWh, 25kWh, 28kWh, 20kWh, 90kWh, 133kWh, 365kWh]	[522kWh, 1196kWh, 583kWh, 30kWh, 42kWh, 45kWh, 125kWh, 198kWh, 28kWh, 750kWh, 702kWh, 625kWh]
$instalCogen$ (cogeneration plants installed)	[0, 0, 0, 0, 0]	[0, 0, 0, 0, 1]	[0, 0, 0, 0, 0]

Table 5.15: Values of the main variables after solving the sizing algorithm of the representative days model on the Potato grower case for both objective functions and their combination

5.6 Global analyses & Selected sizing results

In general, some models presented in this section tend to give more consistent and reasonable results. The model with representative days, especially while maximizing NPV and $NPV - CO_2$, gives bad results. It oversizes the renewable production solutions and the battery capacity to avoid using (bio)gas completely. This might be due to the fact that the assumption over the state of charge of the batteries (the state of charge must be the same at the beginning and at the end of each day) is too strong. Or, since it does not require too many computation resources, the model could be more complex and complete to prevent the algorithm from choosing unrealistic solutions.

In the complete model, reinvestments are enabled to install additional solar panels. However, while analyzing the solutions proposed, one has to be critical-minded. If the algorithm suggests adding only 2 or 3 solar panels every year, it might be better to make a more substantial installation every five years. Some reinvestments proposed might come from the increase in the demand considered in the complete model and the degradation over time of the production solutions. A yearly 2% increase during 15 years implies a significant change at the end.

With more production solutions at the algorithm's disposal, the results might improve, and the oversizing might decrease. But, with the currently proposed solutions and the level of complexity of the models, here are the sizing solutions suggested for each case after the analyses made hereinabove:

- Hypermarket: Solution of the one-year model with CO_2 (Table 5.2) if the demand stays constant or solution of the complete model with NPV (Table 5.1) with a bigger battery capacity if the demand rises significantly. If the latter is chosen, to reduce the carbon footprint of electricity production, those can replace the cogeneration plants with gas with biogas.

- Supermarket: Solution of the one-year model with CO_2 (Table 5.5). If the future demand increases, a slightly bigger wind turbine could be considered (e.g., with a nominal power between 100 and 120kW).

- Concrete producer: Solution of the one-year model with CO_2 (Table 5.8) if the demand remains stable, solution of the complete model with CO_2 (Table 5.7) if the demand grows.

- Sawmill: Solution of the one-year model with CO_2 (Table 5.11) if the demand remains stable, solution of the complete model with CO_2 if one prefers biogas or with NPV if one prefers gas (Table 5.10) if the demand grows significantly.

- Potato grower: Solution of the complete model with CO_2, maybe with a slightly bigger battery capacity.

Obviously, these sizing solutions assume that there will be an intelligent and connected management system to decide at every instant, depending on the demand and the weather, if the electricity produced must be consumed or stored in the batteries, if it is better to discharge the batteries or to use the cogeneration plants, and so on.

In this project, the investment and operational costs can seem very significant, but they would ensure the company's electric operating during the installations' lifetime. In addition, the companies would not receive any invoice from a network provider because it would be totally autonomous. To give an idea to the reader, the price of one MWh of electricity in 2023 is around 250€, even though the reader must remember that these prices are evolving a lot, particularly in the current political and environmental context. The price paid by the Sawmill with an annual consumption of 3000MWh would be around 750,000€ per year. Nevertheless, the financial aspects are not the focus of this master's thesis.

Chapter 6

Conclusion

The objective of this master's thesis was to develop and implement an algorithm for sizing electric production and storage solutions for a tertiary building to become autonomous while minimizing the carbon footprint of the installation. The tertiary building would therefore be an "off-grid" microgrid, a small electrical network not connected to the public grid anymore.

The initial research focuses on microgrids and how to model them, thanks to mathematical programming. To include an environmental analysis of the solutions proposed, an overview of the computation of carbon footprint was given. Moreover, to build the different models that were tested, a reflection on the selection of representative days was made.

Then, the project focuses on the data necessary to test the algorithm provided by the company Broptimize and retrieved on PVGIS. The choice fell on the analysis of five cases, all different in terms of levels or structure of electric consumption. These five cases, denoted by their activity for privacy, were: Hypermarket, Supermarket, Concrete producer, Sawmill, and Potato grower. With the meteorological and hourly radiation data from PVGIS, coupled with the information relative to the wind turbines and solar panels considered, it was possible to compute the expected solar and wind electric production for the five cases.

After the data collection and analysis, the project centered on formulating the mixed-integer programming model (sets, decision variables, parameters, objective functions, and constraints) for the sizing algorithm. This model was implemented in the language Julia, thanks to the JuMP library afterward. It was declined in three versions: a complete model, a one-year model, and a model with representative days, to see the impact of data reduction and on the computational resources required.

The rest of the project focused on the results obtained by applying the three versions of the model to the five cases considered and their analysis. For each case, the three model versions were applied with two different objective functions: maximizing the project's Net Present Value, with a penalization of fuel consumption (financial focus) or minimizing the CO_2 emissions linked to the solution (environmental focus). These two objective functions can be combined by associating a price to CO_2 emissions, such as 100€ per ton, as in this master's thesis. This combination was also used in some tests.

The analysis of the results shows that some pairs of model versions and objective functions give more convincing sizing solutions than others. The representative days model tends to strongly oversize renewable production solutions to avoid installing and using cogeneration plants. Generally, the results obtained while optimizing the Net Present Value or combining the two objective functions are similar. Actually, the best sizing solutions were usually proposed by the algorithm while minimizing the CO_2 emissions. If the company foresees an increase in its electric demand, the results given by the complete model will be more suitable. However, if the demand remains stable or decreases, the sizing of the one-year model is preferable.

Nevertheless, the two smaller models (one-year and with representative days) require far fewer computational resources than the complete one. Therefore, in future developments of this project, more complexity and/or more choices in terms of production and storage solutions could be added to the formulation of the problem to better reflect reality.

In addition, further improvements in the formulation could consider the question of electric vehicles. Their use comes with a non-negligible rise in electric consumption (about 19kWh for 100km). Still, their batteries will offer extra storage capacity in the short term thanks to bidirectional batteries and charging stations.

To conclude, this project provides a formulation of a sizing algorithm and an analysis of the relevance of the results obtained on five cases with different electric consumption profiles. I strongly advise Broptimize to use it and explore the many opportunities for development it possesses in the future.

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[41] *Quel est le (vrai) bilan carbone d'une éolienne ?* URL: https://www.hellocarbo.com/blog/calculer/bilan-carbone-eolienne-etude/.

Appendices

Appendix A

Datasets used & Preprocess

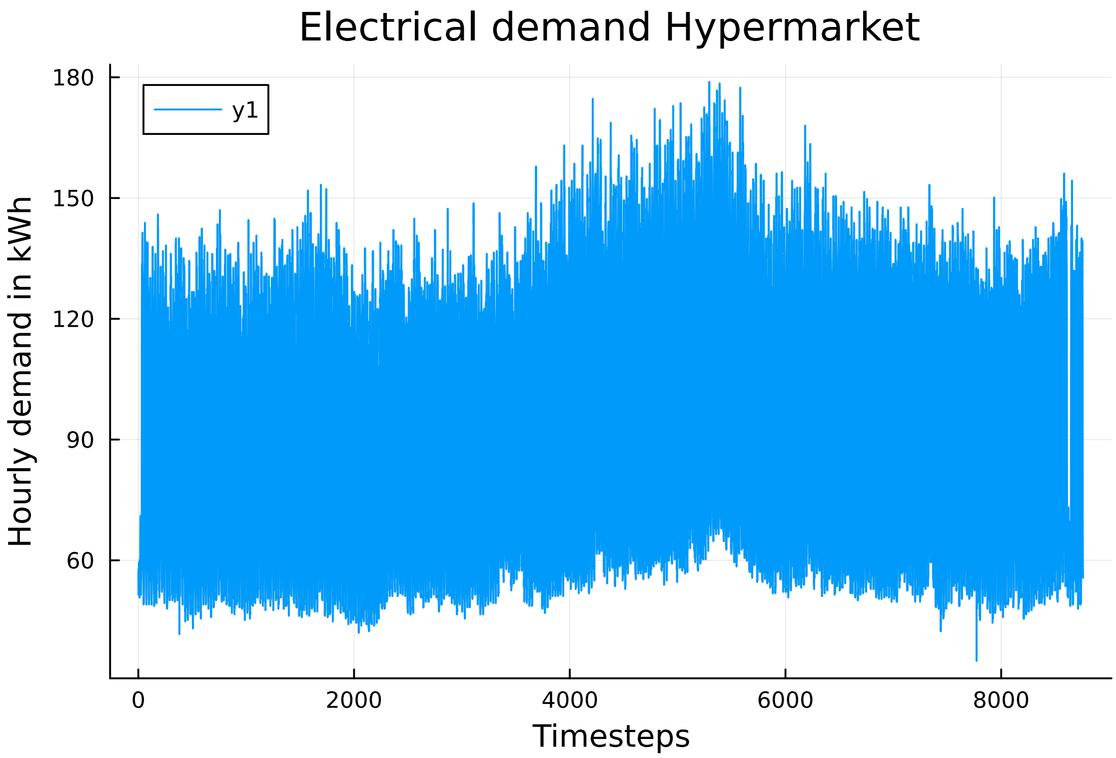

Figure A.1: Hourly electrical demand for Hypermarket

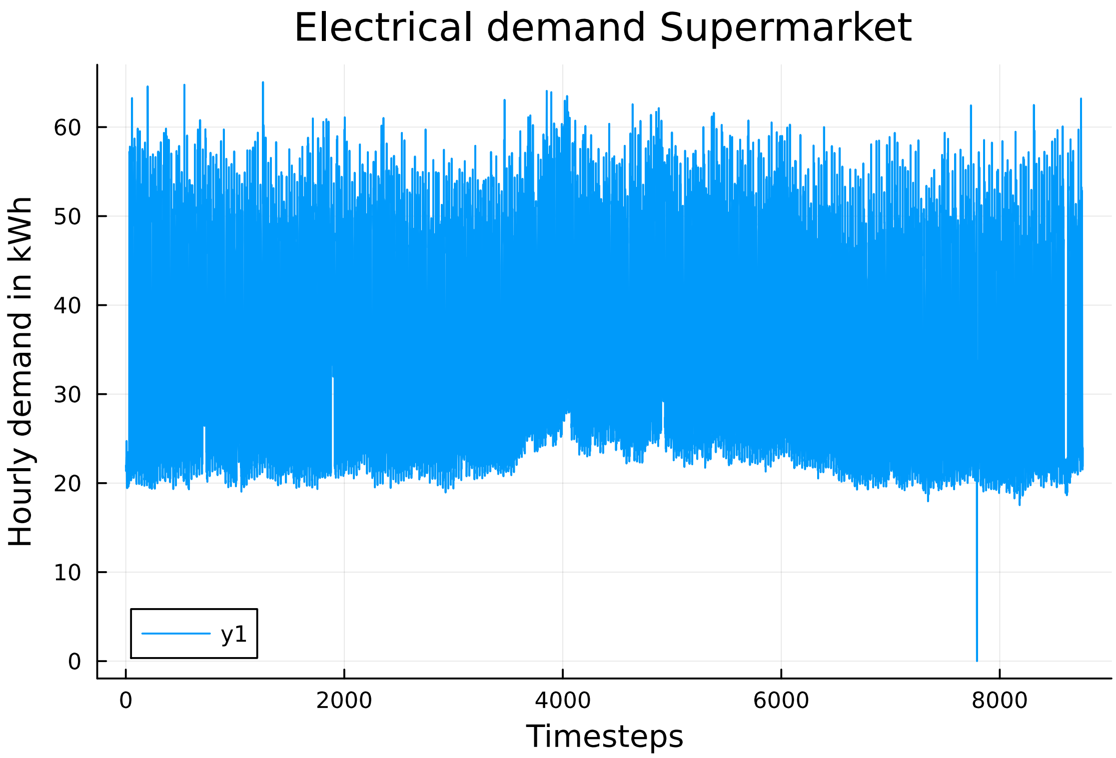

Figure A.2: Hourly electrical demand for Supermarket

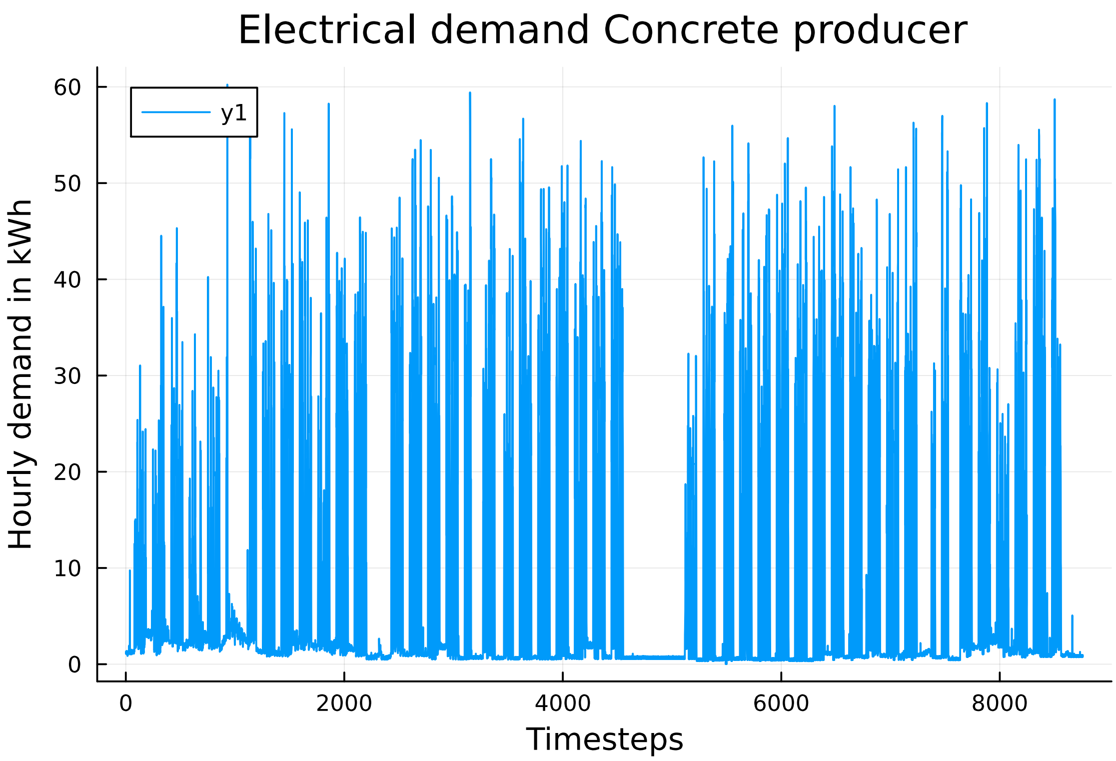

Figure A.3: Hourly electrical demand for Concrete producer

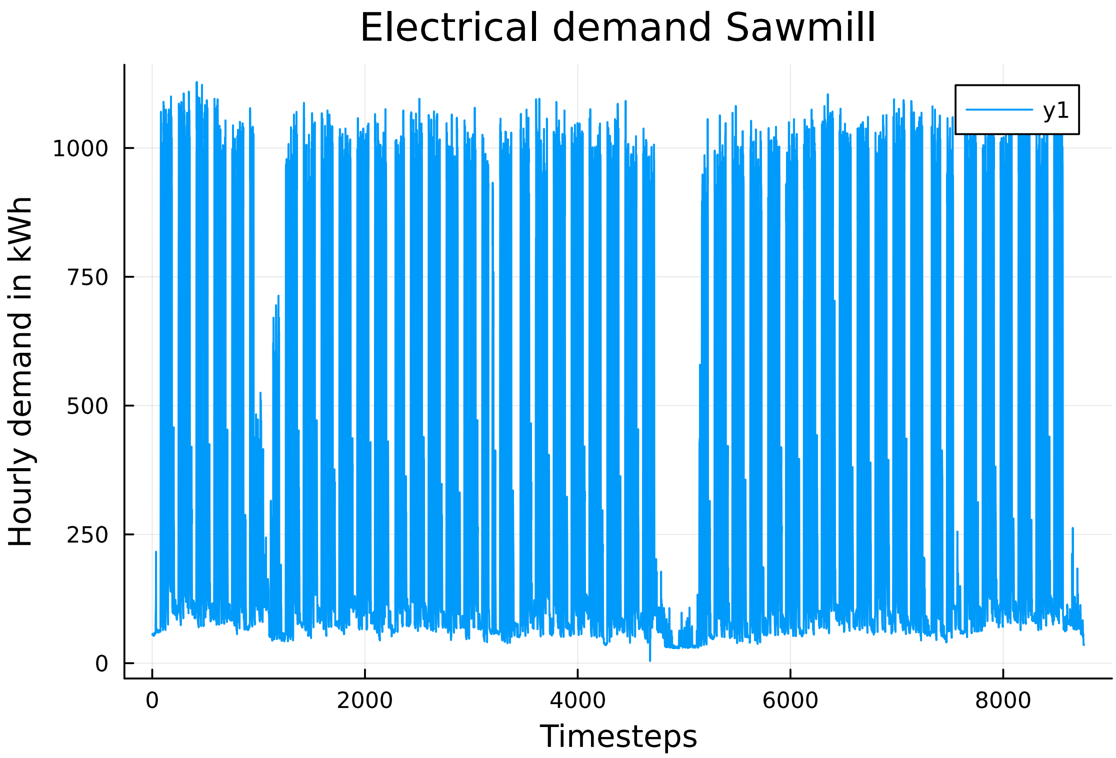

Figure A.4: Hourly electrical demand for Sawmill

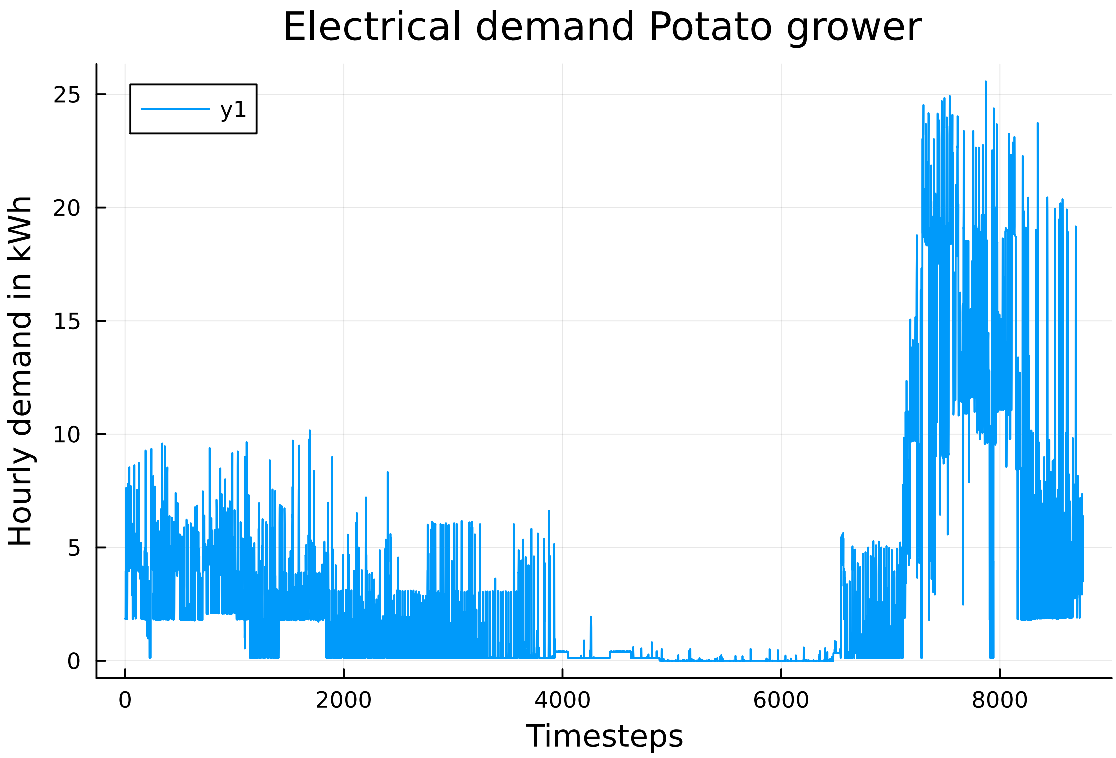

Figure A.5: Hourly electrical demand for Potato grower