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TESI DI LAUREA TRIENNALE IN
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Stochastic assessment of technoeconomic performance on a German carpentry operated as a Net Zero Energy Factory (NZEF)

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Abbreviations

NZEF	Net Zero Energy Factory
EU	European Union
RES	Renewable Energy Sources
PV	Photovoltaic
MC	Monte Carlo
NZEB	Net Zero Energy Building
EVs	Electric Vehicles
BESS	Battery Energy System Storage
PDF	Probability Density Functions
PERT	Program Evaluation and Review Technique
O&M	Operation and Maintenance
FIT	Feed-in Tariff
GHG	Greenhouse Gas
NPV	Net Present Value
MES	Multi Energy System

Abstract

This study explores the uncertain development and the multiples scenarios that a German carpentry can be exposed working as a Net-Zero Energy Factory (NZEF) over a 20-year horizon. This aims to resolve the uncertainty of the industries regarding the profitability of an initial investment and the final sustainability of becoming an NZEF, where the most notable factor of the system is the self-consumption of the electricity generated by the photovoltaic panels installed in the industry.

This will be carried out by a Monte Carlo simulation, in order to consider the uncertainties of the input data within a multiple scenario. This methodology will allow decisions to be made based on two main parameters that are considered determining factors on a long-term view, the cost of energy and the production of CO2.

The results show a value of the two positive parameters, with a considerably reduced CO2 production value. Some components of the parameters present fluctuations but this is offset by the reliability and stability of the results in the long term. This guaranteed reliability in the NZEF concept, both in the self-consumption of renewable energy and in the face of exposure to uncertain scenarios

Introduction

The European Union (UE) has adopted a new adaptation strategy to the impacts of climate change on 24 February 2021. With a deadline of 2050, the main objective is the decarbonization of the energy system. Said adaptation plan is mainly backed by supporting energy generated by Renewable Energy Sources (RES). [1]

Each country of the UE has drawn up action plans to achieve these objectives through the introduction of new policies, generally based on nature-based solutions for adaptation and local adaptation action. For example, thanks to new policies, Italy expects to triple its production of solar energy by 2030, with projections of 55 % of final electricity consumption to come from RES by 2030. [2]

In the same way, Germany has also set new measures in the country's latest energy transition programme. The 2030 indicative national target for the share of renewable energy is set at 30%. In order reach this goal, the country aims to expand the electricity and establish financial incentives aimed at both the heating and cooling, and the transport sectors. [2]

Regarding how these plans are integrated into small and medium enterprises, we must highlight the great increase in the generation of electrical energy from the installation of photovoltaic (PV) panels. Said increase is due to the incentives provided by the state thanks to the sale of surplus electricity generated by PV. It can be said that it may be useful for the next 20 years, since the incentives will be maintained, however after this the sale of electricity to the grid will no longer be rewarded. [3] [4]

In this case, the industry concept of net-zero energy factory (NZEF) can be interesting. The NZEF concept can be defined as the match between the electrical production through RES and the energy consumption of an industrial system. The main objective is to maximize the self-consumption of the factory, thus ending the feeding of the electricity generated into the grid. [5]

It is important to emphasize the significant role of the electric grid, as it plays a crucial role in facilitating the conversion of renewable energy sources (RES) into electrical power. Furthermore, it is often necessary to rely on the existing electric infrastructure to acquire the necessary facilities for RES implementation.

This study will focus on a German carpentry located in Magdeburg. The industry has a photovoltaic plant able to generate up to 126 kW of electric power. The methodology used will seek to explore uncertain multiple scenarios to which the industry may be exposed with a margin of 20 years. This will be carried out thanks to the Monte Carlo (MC) method, filling this gap by providing a general tool for the robust and optimal design of this energy system when limited information is available and it is exposed to uncertainty.

The main parameters that will condition the study are the price of electricity and the amount of CO2, which are the most important parameters for the industry in the near future. This will give a long-term view of the initial investment that it supposes to the industry, their future solvency and sustainability of applying the NZEF concept in a real case.

The thesis will be developed in the chapters mentioned below.

In order to understand the energy concept of industry that is going to be implemented in this study, **Chapter 1** will talk about the concept of Net Zero Energy, its first applications in structures and buildings. Afterwards, this concept will be applied to factories and their current context.

In the upcoming **Chapter 2**, the methodology utilized is introduced in carrying out the study. The methodology is divided into two main parts. The first part concentrates on characterizing uncertain parameters by estimating conditioning parameters for the analysis using distributions, encompassing context parameters and technology factors. The following section of the methodology outlines the process of uncertainty analysis, providing a detailed explanation of how the Monte Carlo method was employed to obtain the study's results.

Chapter 3 delves into the case study, unveiling the practical application of the NZEF concept in a German carpentry. It presents the actual data collected from this case study, along with a comprehensive analysis and its corresponding implications.

Then, in **Chapter 4**, the results obtained from the application of the methodology to the case study will be presented. These results will be analyzed in two sections, the first according to the results of the calculation of the total annual energy cost equation and the second, according to the calculation results of the annual CO2 production equation of the factory.

To conclude, in **Chapter 5** the main objectives are exposed again, a synthesis of the methodology and the results is made. The application of the results and the influence of the study in the current framework.

Chapter 1: Net Zero Energy Factory

This chapter introduces the importance of decarbonizing the network using renewable energy and the concept of Net Zero Energy Factory and its recent applications, in order to put the analysis carried out in context.

Net Zero Energy Factory (NZEF)

Currently, the main objective of the industrial sector is based on the decarbonization of the electrical system, as well as the increase in the use of renewable energies, and the stimulation of the development of sustainable buildings or factories with net zero energy (NZEF).

The "Net Zero Energy" term typically refers to a system, whether residential, commercial, or industrial, where the energy requirements for electricity, heating, cooling, and transportation are met by generating energy on-site, both electric and/or thermal, thus achieving a balance between energy demand and production.

Figure 1 represents a diagram of the operation of a net zero energy building. It shows a two directions grid, which exports and imports electricity from the current. The building is powered by renewable energy sources and, depending on its demand, it exports the excess energy to the network. [6]

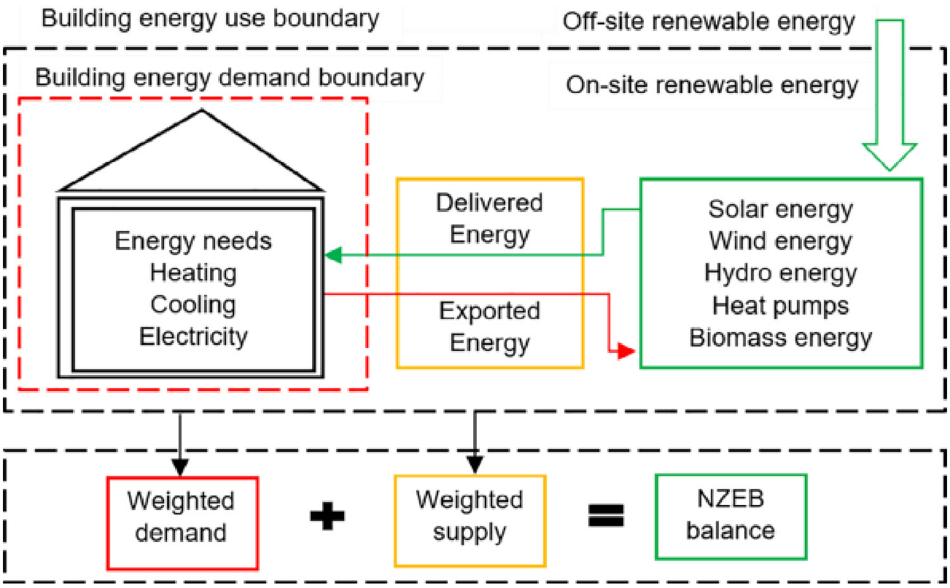

***Figure 1.** Diagram of a Net Zero Energy Building.*

The concept of Net Zero Energy Factory (NZEF) involves aligning the renewable energy sources (RES) generation with the energy consumption of an industrial system. The primary aim is to optimize the factory's self-consumption, eliminating the need to feed the surplus electricity generated back into the grid.

The balance of a NZEF is carried out as shown in Eq. (1):

$$\text{NZEF balance: } |\text{weighted supply}| - |\text{weighted demand}| = 0 \qquad (1)$$

where the difference in absolute values between weighted supply and weighted demand must be zero.

This balance can be represented graphically as shown in **Figure 2**. The position of a reference building is represented in front of a building with a net zero balance. [7]

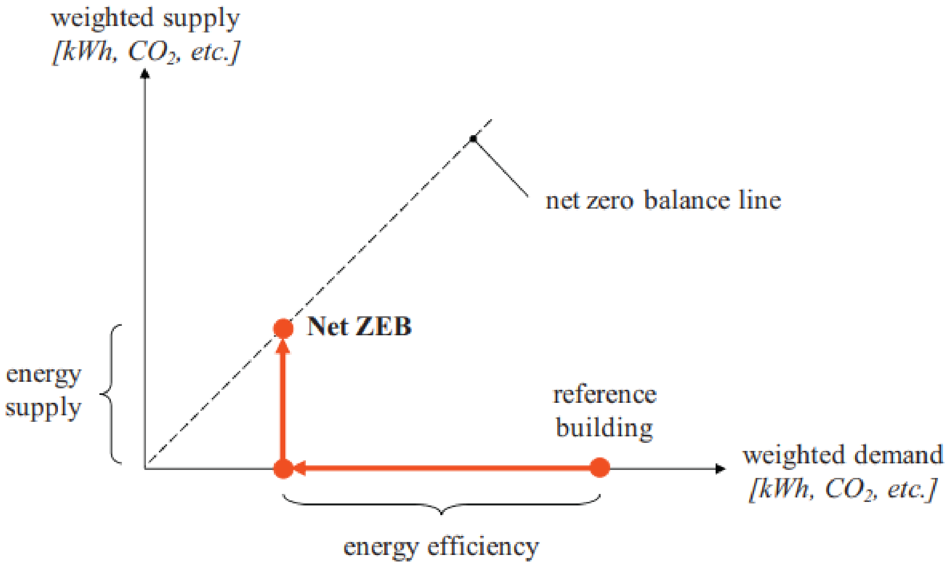

Figure 2. *Graphic representation of the balance of a NZEF system.*

The Net Zero Energy Building (NZEB) concept has garnered a lot of attention in recent years. In the past decades, much reputable projects claiming to achieve a net zero energy balance have been successfully implemented globally. The annual count of completed buildings has consistently increased. Initially, pioneering researchers led the way by realizing exceptional examples. Soon after, environmentally conscious developers and architects began constructing small-scale net zero energy residential buildings. These innovative projects often drew inspiration from subsidized solar electricity generation and showcased significant progress beyond the recently developed passive house concept. [8]

There are several cases where the NZEF concept has already been applied such as [8] and [9]. Most of them are local applications, such as residential applications.

The studies agree on the benefit of implementing this consumption model but, in turn, both agree on the lack of knowledge about the behaviour and economic profitability over a long-term horizon.

However, the application of the concept of net zero energy building in the world of industry is much more recent. The industries supplied in their great majority of renewable energies can adopt this energy model. Notable among the companies that have applied this system are Tesla and Mitsubishi. [10] [11] Both companies use solar energy as RES, thus managing to reduce their emissions considerably and then be able to cover their annual electricity consumption.

The installation of photovoltaic panels in small and medium-sized companies is becoming more and more common, the chosen method is usually *feed it and forget it*. Said method consist in feeding the generated power into the external grid. This operating method is incentivized for a period of 20 years in nearly all European countries. After this time period, PV plants can still supply power to the grid, but operators no longer receive any incentives or are paid a significantly reduced price. For instance, in Germany, the price paid after the incentive period is around 20-25 €/MWh, which is 10-15 times lower than the electricity price paid by a typical residential consumer. This is the reason why the NZEF concept has also gained relative importance. [12]

Furthermore, in this work, the limits of NZEF have been extended in the logistics part, replacing the conventional thermal vehicles with Electric Vehicles (EVs) and adding Battery Energy Storage Systems (BESS) are considered as options to increase the flexibility degree of the manufacturing system.

Regarding on EVs, there are studies that talk about the great benefit of using fleets of electric vehicles in the enterprise such as [13] and [14], achieving a more uniform power exchanged and lowering of the emissions facing different scenarios.

The use of BESS provides the industry with good demand management, energy backup, optimization of self-consumption and, most importantly in our study, integration with the electricity grid.

Chapter 2: Methodology

In this chapter the methodology used for this study will be developed. This methodology aims to explore multiple uncertain scenarios that the industry may face over a 20-year timeframe. To achieve this, the Monte Carlo method will be utilized, addressing the need for a comprehensive tool to effectively design and optimize the energy system under limited information and in the face of uncertainty.

The study will primarily focus on two critical technoeconomic parameters for the industry's future: electricity prices and CO2 emissions. These parameters hold significant importance and will provide insights into the long-term perspective of the industry's initial investment, its future viability, and the overall sustainability of implementing the Net Zero Energy Factory (NZEF) concept in a real-world case.

1. Uncertainty characterization

An Uncertain Characterization refers to the process of determining the unknown parameters of a model and representing them using probability distributions. The most frequently used approach for capturing parameter uncertainty in an energy system design models is through the utilization of probabilistic methods, where parameters are considered as random variables following Probability Density Functions (PDF). [15]

The next section outlines the techniques and data employed in the Uncertain Characterization.

1.1. Input Uncertainty

Accurate quantification of input uncertainties is crucial for obtaining reliable results in an uncertainty analysis, as can be seen in the following study. [16]

To achieve this, we will conduct thorough research of the existing literature in order to accurately quantify the input data. A comprehensive review of the primary literature and techno-economic reports from recent years will be conducted to establish a framework for the upcoming future. This serves as the research objective for this study.

It is important to highlight the socio-political context of uncertainty that the European Union is currently facing in this section.

The EU acknowledge the current energy price scenario, primarily attributed to market gas volatility rather than carbon prices. Within this context, and alongside the rising energy costs, the EU is presently confronted with a multifaceted geopolitical crisis. This crisis not only poses a challenge to the energy transition strategy but also undermines the fundamental aspect of energy security. [17]

Considering this context of uncertainty, a characterization of the context parameters will be carried out in this study. When it comes to technology-related parameters, there is significant uncertainty caused by the continuous evolution and changing nature of technology.

Therefore, all parameters, whether they are related to technology or economics, will be represented as probability distributions with minimum, maximum, and mode values.

1.2.Probability Distribution

As introduced at the beginning of this section, in situations involving uncertainty, probability distributions are used to represent uncertain parameters. These distributions not only capture the possible range of values that a parameter can take, but also account for the likelihood of each value occurring within that range. This is crucial because variations in system operation or environmental conditions are likely to happen with varying frequencies. Therefore, using an appropriate probability distribution to estimate values for an uncertain parameter can significantly enhance the accuracy of predictions concerning the variations represented by that parameter.

For example, using a model that accurately approximates the electricity price at a specific moment implies that any random deviations from the predicted value are likely to occur near this value, while significant deviations are expected to be less common. In this scenario, incorporating a uniform distribution with suitable minimum and maximum values would more accurately capture this pattern of deviations compared to a simple uniform distribution.

This approach greatly contributes to realistically emulating the operation of the system. The design strategy can be implemented using either a deterministic or a stochastic representation of the uncertain parameters. In the deterministic case, a set of discrete points representing fixed parameter values can be used in each iteration. Conversely, in the stochastic case, the set of discrete points is sampled from the employed probability distribution using an appropriate sampling method and thus obtaining significant and logical results in the subsequent simulation with the Monte Carlo method. [18]

In this study, two types of distribution will be used, which are better adjusted to the profile of uncertain data available, the uniform and the PERT distribution.

The **uniform distribution** is defined by the probability density function (PDF) in Eq.2.

$$f(x) = \begin{cases} \frac{1}{2a} & , -a \leq x \leq a \\ 0 & , otherwise, \end{cases} \qquad (2)$$

where $\pm a$ are the limits of the distribution. The probability of lying between $-a$ and $+a$ is constant. The probability of lying outside $\pm a$ is zero. [19]

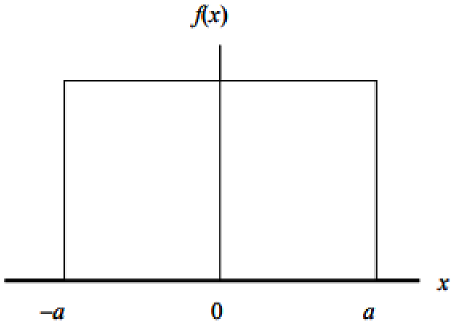

Figure 3. *The uniform distribution.*

Applying the uniform distribution makes it easy to obtain an uncertainty estimate and based on Laplace's original Principle of Insufficient reason, if there is no explicit reason to value one probability distribution over another, a uniform distribution must be used. [20]

The **PERT distribution** can be considered as a particular instance of the Beta distribution, originated from the "Program Evaluation and Review Technique" analysis. It is characterized by defining the minimum, maximum, and most probable values (xmin, xmax, xmode) for the probability density function**.** We opt for the PERT distribution as it is advised for capturing expert information obtained from technical reports, interviews, presentations, and similar sources. Moreover, the technologies we are focusing on exhibit significant variations in input data, such as capital costs, O&M costs, efficiencies, and lifetimes. This necessitates the utilization of PERT distributions for all these parameters. [21]

1.2.1. Context parameters

The context parameters are made up of the electricity prices for non-household consumers, the feed in tariff, the CO2 tax, the discount rate and the grid carbon intensity.

Electricity prices for non-household consumers

Throughout the extended lifespan of a NZEF, prices are anticipated to fluctuate due to numerous influences such as energy markets and energy policies. The precise trajectory of these prices is challenging to forecast, therefore they should be considered uncertain. In this study, the uncertainty surrounding energy carrier prices is addressed by sourcing information from reliable and relevant sources**.**

In order to capture the uncertainty associated with energy carrier prices, we utilize the average value of the two seasons of 2022 Eurostat bands for German non-household electricity, as it can be observed in **Figure 4**, the uncertainty surrounding electricity is quite significant and for this reason it can be approximated to a probability distribution. [22]

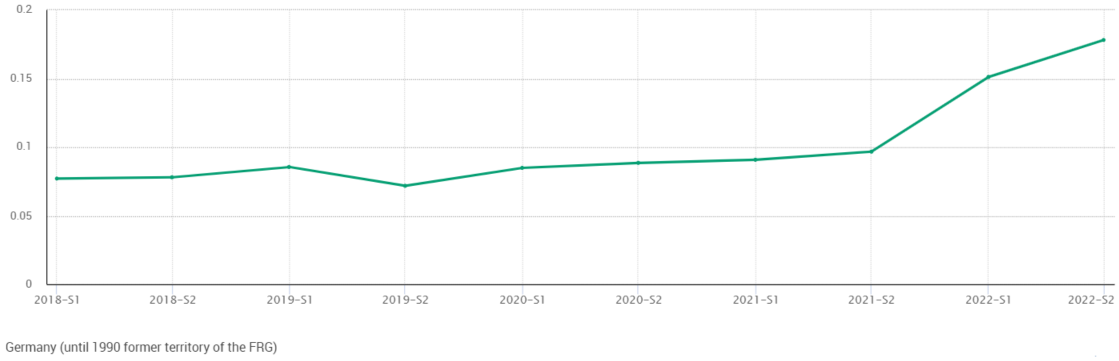

Figure 4. *Electricity prices for German industrial consumers - bi-annual data (from 2007 onwards). Eurostat.*

Various exhaustive studies such as [23], show that various distributions can be applied to estimate the price of electricity in the near future.

In this study we will adopt the previously explained uniform distribution to estimate the behaviour of German electricity prices for industrial consumers over a 20-year horizon. The maximum and minimum values are shown in the **Table 1** along with their corresponding units [€/kWh].

Feed in Tariff (FIT)

The main concept behind feed-in tariff policies revolves around providing assured prices for specific timeframes for the electricity generated from Renewable Energy Sources (RES). These prices are typically offered without discrimination, applying to each kilowatt-hour (kWh) of electricity produced. They can be varied based on factors such as the technology used, installation size, resource quality, project location, and other project-specific variables. [24]

More than 75 countries, states, and provinces have embraced and implemented the feed-in tariff (FIT) mechanism. Within the European Union (EU), 20 out of the 28 members rely on FIT as their primary renewable energy program, while three other states use it for specific technologies. Currently, FIT plays a significant role in promoting renewable energy development in Europe. As evidence of its impact, between 2000 and 2010, the policy facilitated the establishment of over 15,000 MW of solar photovoltaic (PV) capacity. According to a Deutsche Bank report from 2010, FIT accounted for 75% of global PV payments and covered 45% of total global wind energy generation. [25]

Germany’s most recent change to their FIT system was enacted by the German Renewable Energy Act 2014 (EEG 2014). The standard FIT is only available for so-called “small systems” with a capacity under 500 kW. This ceiling fallen to 100 kW in 2016. All other plants must market their solar power directly. The owners of “small systems” can also opt to market their generated electricity directly if they so choose. This FIT functions like the previous FIT, in that 100% of the electricity price goes directly to the power producer. The market premium is calculated every month and involves greater risk. In addition, the intermediary that sells the power on the market may also take a percentage of the price received, so 100% will not go to the power producer.

In our case study, it is a 126 kW carpentry therefore, according to the information obtained from () the FIT value is €0.1071/kWh on October-December 2015, for 20 years, which will constitute the maximum of the uniform distribution. As can be seen in **Figure 5**, the feed in tariff is experiencing a decline, which, starting in 2015 and with a margin of 20 years, will disappear. [26] [27]

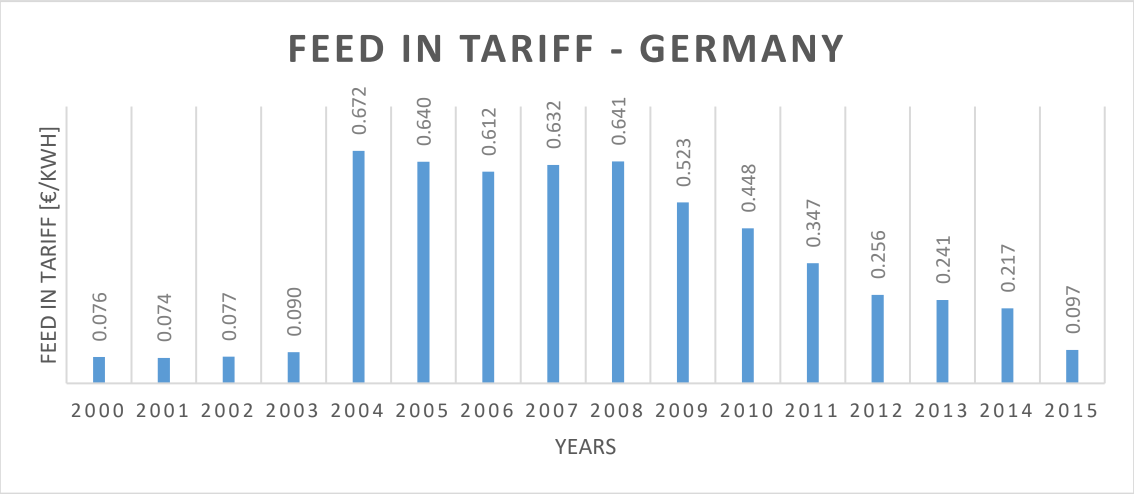

Figure 5. *FIT in Germany for PV production graph over the years (2000-2015)*

After these 20 years, the FIT is expected to be eliminated, therefore we will take the value of 0 as a minimum, as can be seen in **Table 1**, also assigned as a uniform distribution.

CO2 tax

The reality of global warming is now beyond dispute, and its detrimental impact on human beings has emerged as one of the most critical threats worldwide.

The primary human-caused greenhouse gas (GHG) responsible for this phenomenon is CO2, predominantly emitted through the consumption of fossil fuels. According to the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), CO2 accounted for 76% of global GHG emissions in 2004, with fossil fuel usage contributing 56.6% of the total CO2 emissions that year. Faced with the challenge of climate change, the imperative to reduce CO2 emissions and transition towards low-carbon development has become unavoidable, that is why it is one of the main indicators of this study.

Numerous policy approaches have been implemented to curb CO2 emissions, including emission trading systems, emission standards, carbon taxes, and energy taxes. Among these methods, carbon tax stands out as a cost-effective instrument for achieving specific emission reduction targets. Economists and international organizations strongly endorse the implementation of carbon taxes due to their effectiveness. [28]

In Germany, the carbon price will experience a gradual increase, starting at 30 euros in 2022 and progressing to 35 euros in 2023, 45 euros in 2024, and 55 euros in 2025. From 2026 onwards, the fixed pricing mechanism will transition into a price corridor. Within this corridor, the price will fluctuate between 55 and 65 euros, depending on market demand, as shown in **Figure 6**. In 2025, a comprehensive evaluation of the system will take place, allowing for the determination of the trajectory for subsequent years. [29]

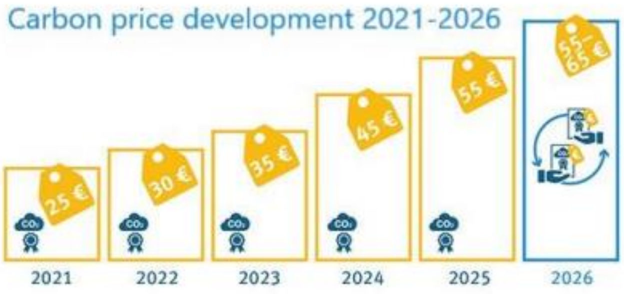

Figure 6. *CO2 tax [€/ tonCO2] development from 2021 to 2026.*

Nevertheless, CO2 certificates are being issued at a consistent price of 30 €/ tonCO2 in 2023, maintaining the same price level as the previous year. This decision aims to protect consumers from the impact of increasing energy prices during the ongoing energy crisis. [30]

Taking all the aforementioned aspects into account, it was decided to adjust the CO2 tax to a uniform distribution, taking the current value of €30/tonCO2 as a minimum and the future value of €65/ tonCO2 as a maximum in 2026, as it is shown on **Table 1**.

Discount rate

The discount rate is employed to adjust all expenses and revenues to their "present values" in order to facilitate comparison. By calculating the present value of the discrepancies between cost and revenue streams, the net present value (NPV) of an option can be determined. The NPV serves as the principal criterion for evaluating the justification of governmental actions. The discounting factor (Dt) required to compute the NPV is expressed as follows:

$$D_t = \frac{1}{(1+r)^t} \qquad (3)$$

where r is the discount rate and t is the time in years. [31]

As a result, there is a lack of certainty surrounding the discount rate in the European context. This uncertainty arises from the observed ranges of the Weighted Average Cost of Capital (WACC) typically used for solar PV and wind projects in different European countries. This information is illustrated by the data provided on the RE-Frame.eu platform, suggesting that a PERT distribution can be employed as an approximation. [32]

To estimate the discount rate in this study, the ETSAP-TIAM model will be used. The Energy Technology Systems Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA), developed the TIMES (The Integrated MARKAL-EFOM System) model generator. The global multiregional model of the TIMES model generator is known as the ETSAP-TIAM (TIMES Integrated Assessment Model). ETSAP-TIAM has a broad scope, encompassing 16 regions worldwide and a time horizon from 2005 to 2100. It also incorporates a climate module with climatic equations, allowing for the evaluation of long-term scenarios related to greenhouse gas emissions.

The ETSAP-TIAM model employs a social discount rate of 5% as a reference. This value is chosen based on a conservative assumption due to the global nature of the model and the varying uncertainties across different regions. When the model invests in different technological options, the risk and uncertainties differ between regions. Consequently, the base risk for Africa is not the same as for Western Europe. It is considered reasonable to have lower discount rates, approximately 3%, in more developed regions, while other regions with higher risks and uncertainties may require a higher social discount rate. Therefore, we will take the value of 3% as the minimum value for the PERT distribution. [31]

It can be said that the determinants of discount rate can be divided between the risk-free rate and risk compensation, which is made up of various factors such as systematic risk, policy risk, technology maturity, among others, as can be seen in **Fig. 7.** [33]

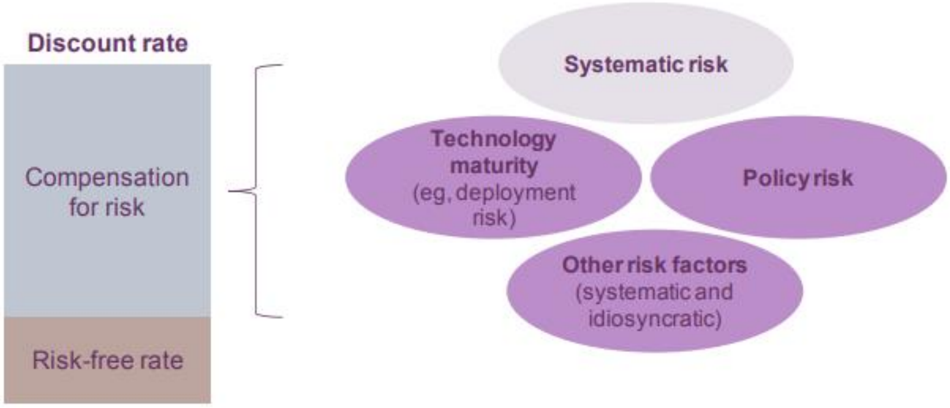

Figure 7. *Determinants of discount rate.*

As a maximum value we will take 9% since it is the highest value for solar PV production according to [33]. Therefore, the value of 6% will be taken as mode. These data can also be seen reflected in **Table 1**.

Regarding the future development of the discount rate, investments in renewable and low-carbon technologies carried out in the next twenty years may exhibit distinct risk-return trade-offs. One key factor influencing this is the evolving government policies, which are expected to impact the risk levels of various technologies based on the market support mechanisms implemented. As a result, certain technologies may become riskier, while others may become less risky.

The estimation of the evolution of discount rates has primarily relied on high-level policy scenarios. In these scenarios, it is assumed that the risk perception of technologies supported by the policy will decrease over time. This reduction in risk perception is then incorporated into the range of discount rates by adjusting the cost of equity, debt premium, and gearing. Additionally, the discount rate estimates are modified for each technology to account for expected changes in the real risk-free rate. According to this approach, technologies benefiting from targeted policies may experience a discount rate that is up to 2-3% lower in the next decade, and potentially an additional 1-2% lower by 2040. Which is already considered between the maximum and minimum values of the study. [33]

For technologies such as batteries and electric vehicles, we will consider an effective life of 10 years, which will be reflected in the final investment cost later developed. Regarding the photovoltaic installation of the factory, it has been estimated a period of life of 20 years.

Carbon Intensity

The grid carbon intensity refers to the amount of greenhouse gases (GHG) released during the generation or consumption of a specific quantity of electricity, as demonstrated by Eq. 4.

$$Grid\ Carbon\ Intensity\ (GCI) = \frac{GHG\ emissions}{Electricity\ amout} \tag{4}$$

GHG emissions are typically measured in grams (g) of CO2 equivalent, and electricity (for example, generated) is typically measured in kWh, the resulting grid carbon intensity is commonly expressed as grams of CO2 equivalent per kilowatt-hour (gCO2eq/kWh). [34]

To obtain the approximate value of the grid carbon intensity, the approximation carried out in the study [35] has been used. Where the zonal weighted average grid carbon intensities for the area of Germany is 538 gCO2-eq/kWh. Instead of utilizing a probability distribution, the study implements the real dataset consisting of average annual values from a provided reference, specifically focusing on European countries, as can be seen in **Table 1**.

In order to calculate the annual CO2 production, it will also be necessary to have the grid carbon intensity of the other components of the factory's energy system. First is the PV carbon intensity, which can be estimated as a uniform distribution. The minimum is considered to be 0, thus assuming a total emissions state of 0. The maximum is considered to be 50 gCO2/kWh based on the following article [36].

Finally, the battery carbon intensity is also estimated as a uniform distribution, taking the value 0 as a minimum, assumed in a zero emissions scenario, and a maximum value of 89 gCO2/kWh, estimated from the study [37].

Context parameter	min	max	mode	[unit]	distribution
Electricity prices for non-household consumers	0.1512	0.1782	-	[€/kWh]	uniform
Feed in tariff	0	0.1071	-	[€/kWh]	uniform
CO2 tax	30	65	-	[€/ tonCO2]	uniform
Discount rate	3	9	6	[%]	PERT
Grid Carbon Intensity	538	-	-	[gCO2-eq/kWh]	European regional set
PV Carbon Intensity	0	50	-	[gCO2/kWh]	uniform
Battery Carbon Intensity	0	89	-	[gCO2/kWh]	uniform

Table 1. *Context parameters with minimum maximum and mode according to uniform and PERT distributions.*

1.2.2. Technology parameters

The parameters pertaining to the technology are outlined below. The primary focus of the study is centred around a specific factory that utilizes photovoltaic panels to generate electricity, employs batteries for energy storage, and employs electric cars for transportation purposes. The details and attributes of these resources will be elaborated upon in the chapter dedicated to the case study. The primary objective of this section is to provide an explanation of the expenses associated with these technologies, encompassing both the initial investment costs as well as the ongoing maintenance expenses.

Solar Photovoltaic (PV)

The photovoltaic panels are used to generate electricity for the factory's self-consumption. The cost of a photovoltaic panel system can fluctuate based on its capacity, as higher capacity generally corresponds to higher associated costs. While this study does not emphasize the initial investment cost of the pre-installed photovoltaic system, as it does not factor into the annual cost calculation pertinent to this study, it does place emphasis on the operational and maintenance costs (O&M), which do impact the techno-economic analysis. Since the O&M costs is multiplied by the Capital Cost, finally the Capital Costs of the photovoltaic installation will be necessary, which follows a PERT distribution, as shown in **Table 2**.

Within the O&M costs, both operating and maintenance expenses are considered. Operating expenses encompass various aspects such as operations management, conductive operations, directions for work performance, monitoring and operator knowledge, protocols and documentation. As for maintenance costs, maintenance administration, preventive maintenance, corrective maintenance, and Condition-based maintenance can be highlighted. [38]

The O&M costs have been estimated through different articles reflected in the following study [35]. It has been estimated that this parameter follows a PERT distribution, which is composed of the maximum, minimum and mode values, shown in **Table 2**.

Li-Ion battery

Li-ion batteries are used by the factory to store excess energy for later use. In this case, the investment capital cost is considered, which follows a PERT distribution, as shown in the aforementioned study [35]. **Table 2** displays these values with their corresponding units.

Electric Vehicles (EVs)

In order to optimize and reach the NZEF objective, the factory has replaced its conventional vehicles with electric vehicles. Said investment requires a cost of capital which is estimated by means of a PERT distribution. Said distribution is characterized by a minimum value and a maximum value, which correspond to the minimum and maximum value of the price of a vehicle according to the study [39]

Technology parameters	min	max	mode	[unit]	distribution
Solar Photovoltaic (PV)					
Capital costs	639	2038	1290	[€/kWh]	PERT
O&M costs	0.5	5	1.5	[%]	PERT
Li-ion battery					
Capital costs	149	598	285	[€/kWh]	PERT
Electric Vehicles					
Capital costs	35000	50000	-	[€/vehicle]	PERT

Table 2. *Technology parameters with minimum maximum and mode according to PERT distribution.*

In addition to all this, you must count on the investment of the charging stations for electric vehicles, which corresponds to 8,000€ per year for two charging stations of 22 kW each, as estimated in the analysis of the same work. [39]

Regarding the O&M costs related to batteries and electric vehicles, as well as charging stations, a total cost of 1970€ per year can be considered, based on the same study.

2. *Uncertain analysis*

The subsequent section provides a comprehensive account of the uncertainty analysis conducted using the Monte Carlo method. The purpose of this stochastic analysis is to determine the total annual cost and the total annual CO2 production by employing random scenarios generated through this method. These calculations are aimed at generating an output distribution for a 20-year time frame, which will subsequently be subject to a thorough analysis to derive detailed insights from the obtained results.

Monte Carlo simulations

Stochastic planning models generally prioritize long-term investment strategies spanning several years or even decades. These models recognize the significance of incorporating operational considerations that can impact and be influenced by strategic decisions. To identify robust, adaptable, and financially viable solutions, it becomes essential to evaluate the utilization of the infrastructure, its associated costs, and its ability to adapt to changing circumstances. [40]

For this study, therefore, the Monte Carlo method has been chosen. MC is a statistical technique that utilizes random input values from specific parameters to generate a distribution for the output parameter. Random values are generated by the random function for a given distribution in MATLAB. Within the previously specified minimums and maximums, the function is responsible for generating a random number. This randomness is what this study seeks, since it represents a simulation of the behaviour of the parameters of interest in different scenarios, thus allowing the analysis of parameters that affect the operation and profitability of the factory.

Each scenario generated by MC represents a unique combination of values for the input parameters. By conducting multiple iterations of the MC simulation, a broad range of possible outcomes is generated over the 20-year time horizon. This enables the analysis and understanding of the result distribution, identification of favourable and unfavourable scenarios, and assessment of the factory's robustness and flexibility in varying conditions. [41]

MC analysis has been applied to similar studies in recent years. We can find various articles in the literature where this method is chosen for its practicality in long-term horizons. [40] [42] [43]

Within the MC analysis, two crucial operations will be carried out to obtain the desired results. Firstly, the value of the annual cost and secondly, the value of CO2 produced by the factory in one year.

To determine the annual cost, the calculation begins with assessing the investment cost associated with batteries and electric vehicles. However, the investment cost of the photovoltaic installation is excluded from consideration as it was already incurred by the factory in a prior period, as explained in the preceding section.

The units of each parameter have been specified in **Table 1** and **Table 2**, while those corresponding to the case study will be explained in the case study chapter.

As shown in **Eq. 5., Eq.6** and **Eq.7.**, the investment cost is calculated by multiplying the random value generated by the capital cost distributions of the storage system, electric vehicles and PV installation respectively, by the battery capacity and the number of electric vehicles. The specific values of the case study will be specified in the case study section.

$$\boldsymbol{Invest\ Cost\ Storage\ System}[€] = (Capital\ Costs\ Storage * Battery\ Capacity\ Storage) \quad (5)$$

$$\boldsymbol{Invest\ Cost\ EV}[€] = (Capital\ Costs\ Vehicle * number\ of\ vehicles) \quad (6)$$

$$\boldsymbol{Invest\ Cost\ PV}[€] = (Capital\ Costs\ PV * PV\ Power) \quad (7)$$

The annual investment cost is finally calculated in **Eq. 8.** by applying the discount rate as reflected in the following equation, where the time in years (t) is 10, for the estimated life of storage technologies and electric vehicles, and 20 for the PV instalation.

$$\boldsymbol{Annual\ Invest\ Cost}[€] = Invest\ Cost * \frac{Discount\ rate*(1+Discount\ rate)^{t}}{(1+Discount\ rate)^{t-1}*(1+Discount\ rate)} \quad (8)$$

Next, the annual cost of maintenance and operation of the photovoltaic installation is calculated. In **Eq. 9.** this calculation is made. The power of the photovoltaic installation is multiplied by the initial investment of the installation (after applying the discount rate) by the percentage of the O&M costs. Said percentage of O&M costs is divided by 20 since the cost for one year is calculated in the equation.

$$\boldsymbol{PV\ annual\ cost}[€] = PV\ Power * Capital\ Costs\ PV * O\&M\ costs/20 \quad (9)$$

Finally, the total annual cost can be calculated using **Eq. 10.** In this equation made by five components, the price of electricity is multiplied when buying it by the energy purchased by the factory, minus the Feed in tariff multiplied by the excess electricity sold to the grid by the factory, plus the multiplication of the CO2 tax by the Grid carbon intensity (multiplied by 10^ [-6] for its corresponding change of units to gCO2/kWh) and the energy purchased by the factory. To all this will be added the O&M cost related to batteries and electric vehicles (specified in the previous section), the annual investment cost of EVs and Battery and the annual cost of the PV.

$$\boldsymbol{Annual\ Cost}\ [€] = (Electricity\ Price * Energy\ Buy) - (Feed\ in\ Tariff * Energy\ Sold) + (CO2\ tax * Grid\ Carbon\ Intensity * 10^{-6} * Energy\ Buy) + O\&M\ costs + EV\ annual\ invest\ costs + Battery\ annual\ invest\ costs + PV\ annual\ costs \qquad (10)$$

The calculation process involved determining the average value of individual parameters. Consequently, the **Eq. 10.** has been evaluated on five separate occasions, because of its five components. The O&M costs component is not considered since it does not follow a distribution, it is a fixed value, as explained previously. In each formula, the mean value of all the components except one has been taken, from which its variation will be analysed. This approach allows for an examination of how the annual cost varies based on each component of the equation. The results of these equations will be presented in the results chapter.

The next determining parameter for the analysis is the annual production of CO2 by the factory in one year. Said parameter is calculated with the sum of the three multiplications of each carbon intensity by its corresponding energy, shown in **Eq. 11**. The multiplication of the Grid Carbon Intensity by the energy purchased from the grid, plus the multiplication of the PV carbon intensity by the energy generated by the photovoltaic panels, plus the Battery Carbon Intensity multiplied by the battery charging energy.

$$\boldsymbol{CO2\ annual\ production} = (Grid\ Carbon\ Intensity * Energy\ buy) + (PV\ Carbon\ Intensity * Energy\ PV) + (Battery\ Carbon\ Intensity * Battery\ charging\ energy) \qquad (11)$$

Eq. 11. is therefore made up of 3 components, from which their corresponding mean value has been calculated. **Eq. 11**. is carried out three times, with all the mean values of the components except one, of which its corresponding variation and influence on the annual production of CO2 will be analysed in the results section.

Once the equations that determine the significant parameters of the analysis are available, the Monte Carlo simulations can be carried out, whose process will be developed with the MATLAB tool. These simulations will be carried out thanks to a for loop which will go from 1 to 500 iterations.

In each MC iteration, a collection of input parameters is randomly chosen based on their probability distribution. Once the input parameters are sampled, the optimization problem is solved, and distributions of the total annual cost, and CO2 annual production are generated. These distributions enable decision-makers to assess the variations in the optimal MES design considering the uncertainties in the input parameters. These distributions allow making the pertinent decisions and evaluating the variations considering the uncertainties in the input parameters.

Chapter 3: Case of Study

In this chapter, an overview of the framework will be presented, introduce the real case where this study has been conducted, highlight its main characteristics, and discuss the collection and analysis of real data obtained from the actual case, which will shape the scope of this study.

1. German Carpentry

A carpentry factory has been considered for this study. The factory called aRTE möbel GmbH is in the town of Magdeburg (Germany), dedicated to the manufacture of custom furniture.

***Figure 8**. German carpentry case of study "aRTE möbel GmbH".*

The carpentry has a 126-kW photovoltaic installation which produces electricity for the factory's own consumption. To synchronize the timing of the generated power, it is initially introduced into the grid and subsequently withdrawn from the grid to meet the needs of industrial processes. Regarding the input data of the photovoltaic installation of the factory, we highlight the power generated by the installation each month of the year, with units of kW. It can be said by analysing the data acquired, the power generated increases in the months with the greatest exposure to the sun, while it decreases in the months with fewer hours of sunshine per day.

The following graph makes a comparison of the energy production generated in a week in December (indicated by the orange colour) and a week in August (indicated by the blue colour). The y-axis is expressed in kilowatts [kW] and the x-axis through time intervals which are taken every 15 minutes within a week of the month. Thanks to this comparison, it can be confirmed that indeed the production during the month of December is much lower than the production in the month of August.

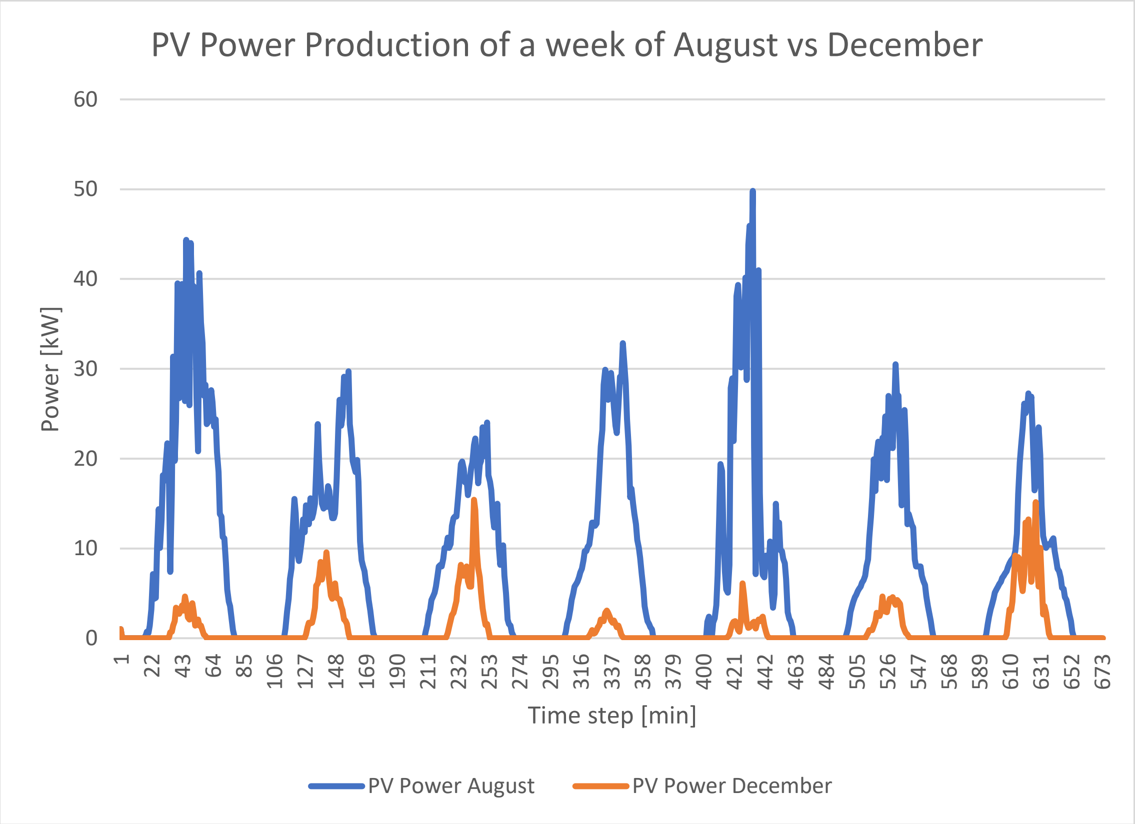

Figure 9. *Graph on the comparison of the production of the PV installation for a week in the months of August and December.*

For the reason stated above, the factory will need to buy electricity from the grid at times when the production of the PV installation does not generate the necessary energy. In turn, in the months of greatest energy production, in order to store energy for later use in times of need, storage systems such as Li-ion batteries will be used, in addition to selling to the grid. These aspects will be explained below.

The other main component of the factory is the Battery Energy Storage System (BESS). Recently, there has been an increasing use of energy storage in the distribution network to improve the reliability and consistency of electricity supply. It is also used to ensure the continuous operation of both conventional and renewable energy sources. Since one of the main objectives of this thesis is to provide a solution to the fluctuation and uncertainty of renewable sources in order to become an NZEF, batteries are a crucial element in the factory's energy system.

Li-ion batteries are used in this factory, the charge and discharge values of used Li-ion batteries have also been obtained. Two battery systems have been installed. They allow the storage of up to 50 kWh of electricity with a maximum power of 20 kW.

Numerous studies have demonstrated the tangible advantages of collaborating between energy storage systems and volatile energy sources, such as photovoltaic (PV). Through the implementation of suitable algorithms and a well-designed control system, it becomes feasible to enhance the functionality of the PV system, allowing it to provide valuable system services. However, realizing these potential benefits necessitates the effective management of both energy sources and storage units as an integrated unit. [44]

Figure 9 illustrates a comparison between the load profiles of the Battery Energy Storage System (BESS) for a week in August and a week in December. The y-axis represents the energy value in kilowatts [kW], while the x-axis represents time values in 15-minute intervals throughout a week in a specific month of the year.

This chosen representation serves to demonstrate the utility of batteries during months with high energy production, as they enable substantial energy storage, preventing excess energy from being sold to the grid and supporting the objective of achieving a NZEF. Conversely, during months with lower energy production, the battery charge level is considerably reduced.

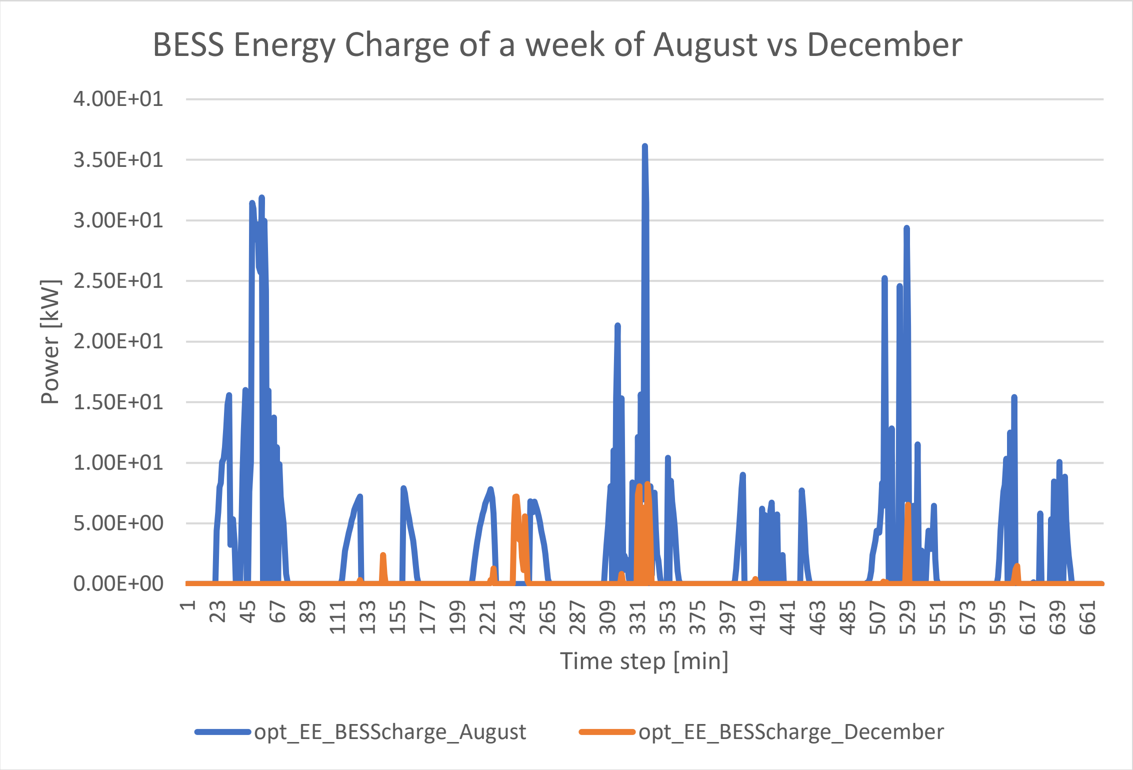

Figure 10. *Battery Energy System Storage charging profile of a week of August vs December.*

In line with the preceding graph, **Figure 10** displays the discharge behaviour of the BESS during a week in the months of August and December. The y-axis represents the discharge value in kilowatts (kW), while the x-axis denotes 15-minute intervals throughout the week. This graph clearly demonstrates that during months with abundant solar energy production, the utilization of batteries is minimal. However, in December, when solar production is substantially reduced, the energy consumption (i.e., discharge value) of the batteries significantly increases. By leveraging the stored energy within the batteries, the need to purchase energy from the grid is avoided.

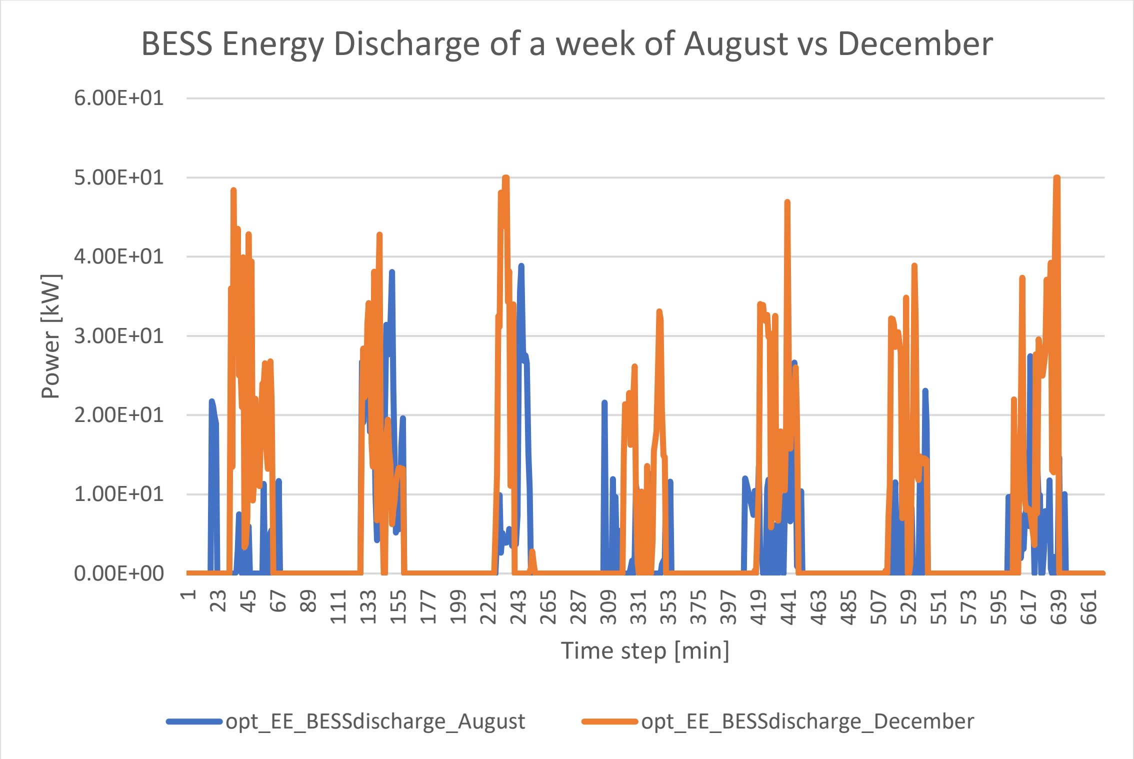

Figure 11. *Battery Energy System Storage discharging profile of a week of August vs December.*

The input data for the analysis includes the energy purchased and sold from the electricity grid, expressed in kilowatts (kW). Upon examining the data, it is evident that the values for electricity purchase and sale are quite similar. This suggests that the buying and selling of electricity from the grid is not a primary function of the factory. This finding further reinforces the objective of achieving the NZEF, which entails reducing dependence on the grid and prioritizing self-consumption.

The final component of the case study that impacts the techno-economic analysis is the integration of electric vehicles. The factory has made the decision to transition from conventional vehicles to electric vehicles. The factory currently has five electric vehicles, and although their charging profile data is available, this study will not analyse the charging power of the vehicles. Instead, the focus will be on the pertinent parameters of the electric vehicles, namely the investment cost and the O&M costs, which have already been discussed in the methodology section.

Once the data provided by the factory has been analysed, it is concluded that they have been well taken and are correct, since they represent the reality to which the factory is exposed. These data have been taken as real input data, which do not follow a distribution, as explained in the methodology section.

Subsequently, the methodology described in Chapter 2 is implemented utilizing the provided essential data. This methodology enables the assessment, within the scope of the case study, of the resilience range against external fluctuations. Specifically, it examines the uncertain data represented as distributions, considering exposure to various uncertain scenarios and the range of compliance. The objective is to determine the extent to which achieving NZEF is feasible, considering the challenge posed by fluctuating renewable energy generation. Once the methodology has been implemented, the resulting outcomes will be presented along with their respective conclusions.

Chapter 4: Results

In this chapter, the outcomes derived from the implementation of the methodology in the case study will be showcased, followed by a meticulous analysis to derive the corresponding conclusions. The chapter will be divided into the two main objectives of the study, the result of the calculation of the total annual cost and the annual production of CO2.

1. *Results of the Monte Carlo Analysis*

As described in the methodology section, this study utilized the Monte Carlo method with 500 iterations to calculate the two key determining parameters. Equations within the loop were employed to calculate these parameters. Each component of the equation was separately analysed to assess its impact on the total result of CO2 production and annual cost.

The annual production equation consists of five components. Each component was examined individually, resulting in a total of five equations. The purpose was to observe the variation of each component. The total annual cost is influenced by various factors, including fluctuations in grid cost, CO2 tax, investments in photovoltaic (PV) systems, investments in battery energy storage systems (BESS), and investments in electric vehicles (EVs). For each equation, the mean of the parameters not under analysis was taken, while the mean of parameter being analysed was excluded, allowing for an assessment of its influence on the main equation. Once the five equations were completed, the results were obtained and subsequently analysed.

The same methodology is applied to examine the annual production of CO2, which involves an equation comprising three parameters that affect the production. To analyse the impact of each parameter individually, three separate equations are employed, with one equation dedicated to calculating the CO2 production for each parameter. In each equation, the mean values of the parameters that are not under analysis are utilized, while the mean value is not considered for the parameter being analysed. By employing this approach, the influence of the Grid Carbon Intensity, PV Carbon Intensity, and Battery Carbon Intensity on the annual CO2 production can be analysed comprehensively.

Once the 500 interactions have been completed, the results are obtained. In order to analyse the influence of each parameter, the box plot representation has been chosen, which consists of a rectangular box and "whiskers" that extend from it. The box represents the interquartile range (IQR), while the whiskers depict the variability beyond the IQR. Additionally, any outliers are represented individually as points or asterisks. This visual representation allows for a comprehensive understanding of the distribution and comparative analysis of the results for each parameter.

Below in the **Figure 11** is a schematic boxplot where each relevant element of the box scheme is shown, as long as it is easier to interpret the results. [45]

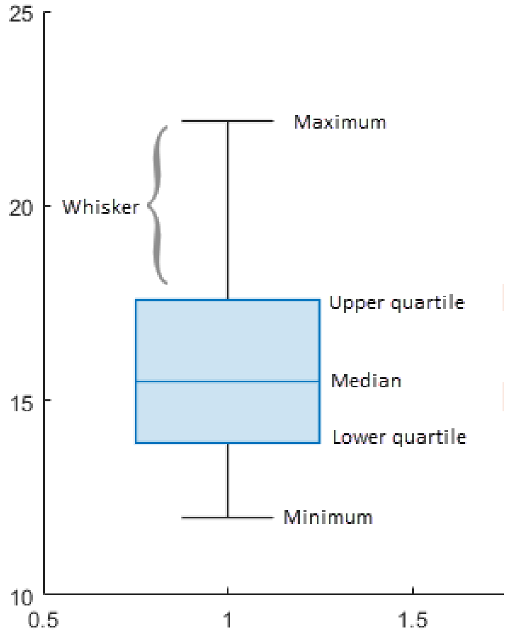

Figure 12*. Description of a box plot in MATLAB.*

The median is the horizontal line inside the rectangle at the center of the box plot represents the median, which is the value that divides the dataset into two equal parts. It provides a measure of the central location of the data.

The box in the box plot represents the interquartile range (IQR), which extends from the first quartile (Q1) to the third quartile (Q3). The IQR shows the variability of the data and the dispersion of the central set of values.

The whiskers usually represented by vertical lines that extend from the box, indicate the dispersion of the data beyond the interquartile range. They can help identify outliers or extreme values.

Finally, the outliers are the individual points outside the range of the whiskers and may require special attention during analysis. In the context of a NZEF, outliers could represent unusual situations in terms of energy consumption or production.

Additionally, this box plot visualization method allows us to observe the distribution of the data for both parameters. It reveals that most of the data points for each factor are concentrated in the central part of the box, indicating a clustering of values around the median. This suggests that the annual costs for these factors tend to have a more consistent and predictable pattern.

On the other hand, the presence of outliers, represented by individual data points outside the whiskers, indicates the occurrence of abnormal or extreme values. These outliers represent instances where the annual cost deviates significantly from the typical range of values. These outliers could be attributed to exceptional circumstances, unexpected events, or unique situations that impacted the cost of the net zero factory during specific years.

Once the method of interpretation of the results has been exposed, the results of the study will be presented.

1.1. Annual Total Cost Production

The following box plot, **Figure 12**, made in MATLAB is constituted by the five components of the equation of total annual production cost of the factory, these are the fluctuations in grid cost, CO2 tax, investments in photovoltaic (PV) systems, investments in battery energy storage systems (BESS), and investments in electric vehicles (EVs). This graph will be analyzed following the component script explained above.

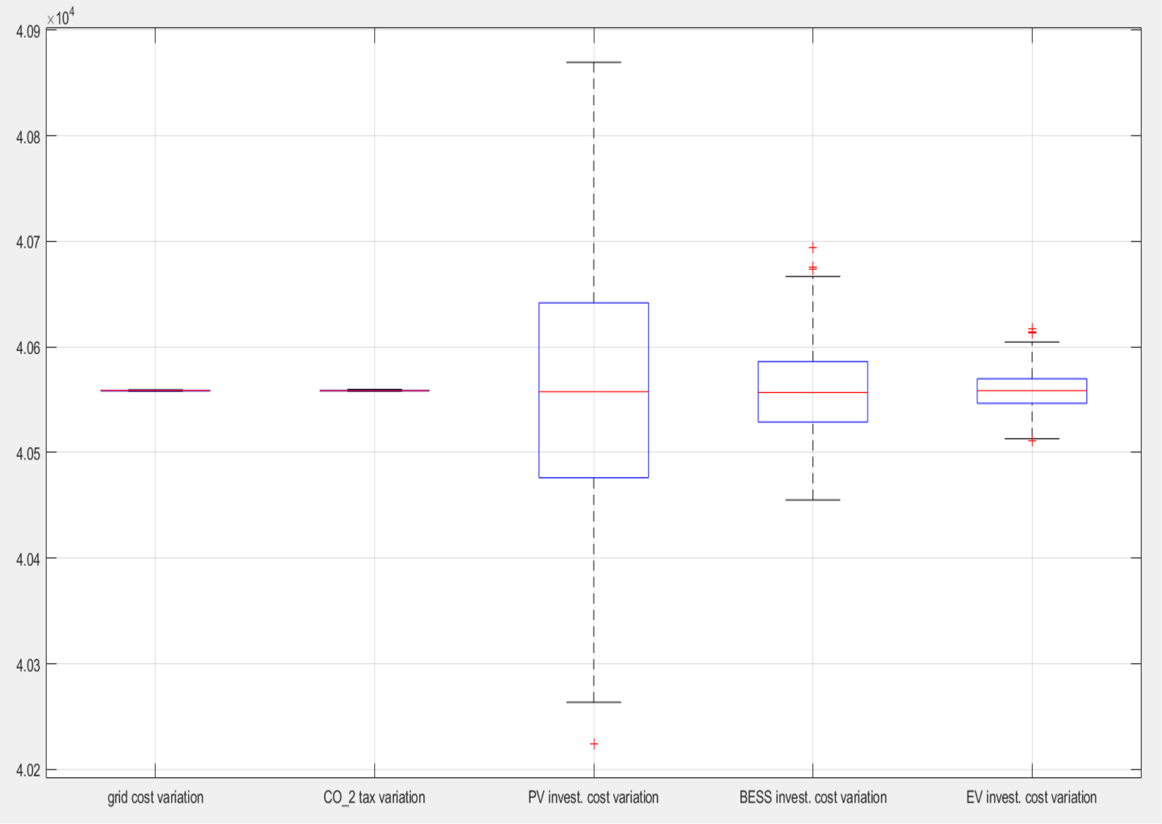

Figure 13. *Annual Total Cost Production Box Plot.*

The median value of each component is shown in the **Table 3**. As can be seen, the value is practically the same with the variation of the five components of 40557.98€ per year.

In the case of a medium-sized carpentry factory, the annual cost of 40557.98€ seems to be suitable and falls within the expected range. This amount translates to approximately 3379.832€ per month in energy expenses. When compared to similar factories, this level of consumption is considered appropriate for a carpentry business of this nature. It indicates that the factory is operating efficiently and managing its energy consumption effectively working as a NZEF.

As has been observed, the median of the five components remains stable. In this context, having the same median in all the savings banks implies that the central value of the annual costs remains constant throughout the period analysed, during the 20 years. This indicates some stability in the total annual costs of the factory, regardless of the factors represented by each box. Although individual costs may vary among the different factors, the constant median suggests a consistency in the central value of the costs.

Components of the Annual Total Cost	**Median**	**[Units]**
Grid cost variation	40558.687	€/year
CO2 tax variation	40558.656	€/year
PV invest cost variation	40556.9486	€/year
BESS invest cost variation	40556.9486	€/year
EV invest cost variation	40558.6615	€/year
Mean value	40557.98034	€/year

Table 3. *Median values of the Annual Total Cost Components.*

It is important to analyse the factors represented by each box to understand the variations in annual costs and how they influence the median. By doing so, a more complete picture of what specific factors contribute to the differences in costs can be analysed and how they are distributed within the data set.

The difference in the size of the boxes and whiskers between the different boxes indicates variability in annual costs due to different factors. Boxes with a larger size and more extended whiskers indicate a greater dispersion and variability in the costs associated with these factors compared to smaller boxes.

Afterwards, each individual component will be examined to understand its impact on the overall annual cost.

Grid Cost Variation

Figure 14 displays an enlarged view of the grid cost variation in relation to the total annual cost of the factory. It is evident that this specific factor is represented by a small box with short whiskers, indicating its lower variability in annual costs compared to the other factors represented by the remaining boxes. Consequently, the total annual cost of the factory remains relatively stable over the course of 20 years, with no significant fluctuations attributed to grid costs.

This observation suggests that this factor has a more controlled and predictable influence on the factory's annual costs. It may represent a management area characterized by stability or exhibit reduced vulnerability to external changes, distinguishing it from the other factors.

This suggests that the price of electricity remains relatively constant over the 20 years, compared to the other factors. This may reflect greater control or stability in the price of electricity, less exposure to fluctuations in the energy market, or effective management of electricity consumption in the factory.

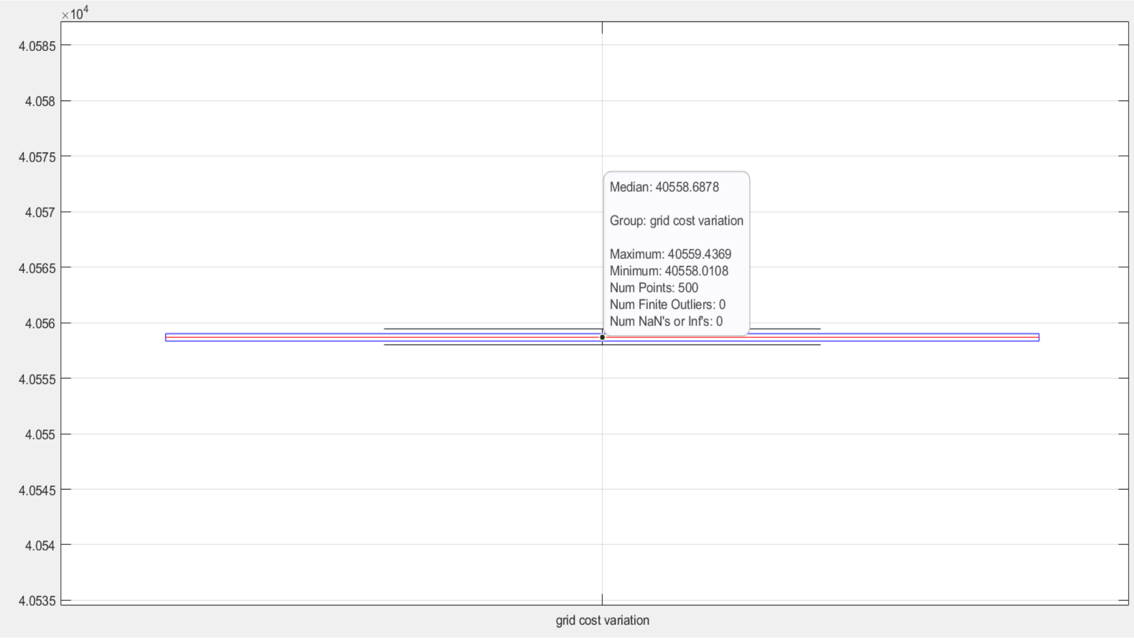

Figure 14. *Box plot of Grid Cost Variation.*

CO2 Tax Variation

Figure 15 shows the expansion of the CO2 tax variation in relation to the total annual cost of the factory. The presence of a small box with short whiskers for the CO2 tax indicates that this factor exhibits less variability in annual costs compared to the other factors represented by the remaining boxes. Consequently, the economic impact of the CO2 tax remains relatively stable over the 20-year period, without significant fluctuations, like the previously mentioned variation in network costs.

This observation suggests that the CO2 tax is consistently applied throughout the analysed period. It also implies that the factory has successfully implemented effective strategies and measures to reduce its CO2 emissions, resulting in more consistent costs associated with the tax, achieving the NZEF objective. This will be analysed in depth in the analysis of the annual production of CO2.

Additionally, the small size and short whiskers of the CO2 tax box may indicate a lower level of price or regulatory volatility regarding CO2 taxes within the business and regulatory environment where the factory operates. This provides a degree of stability in costs and enables improved financial planning and management.

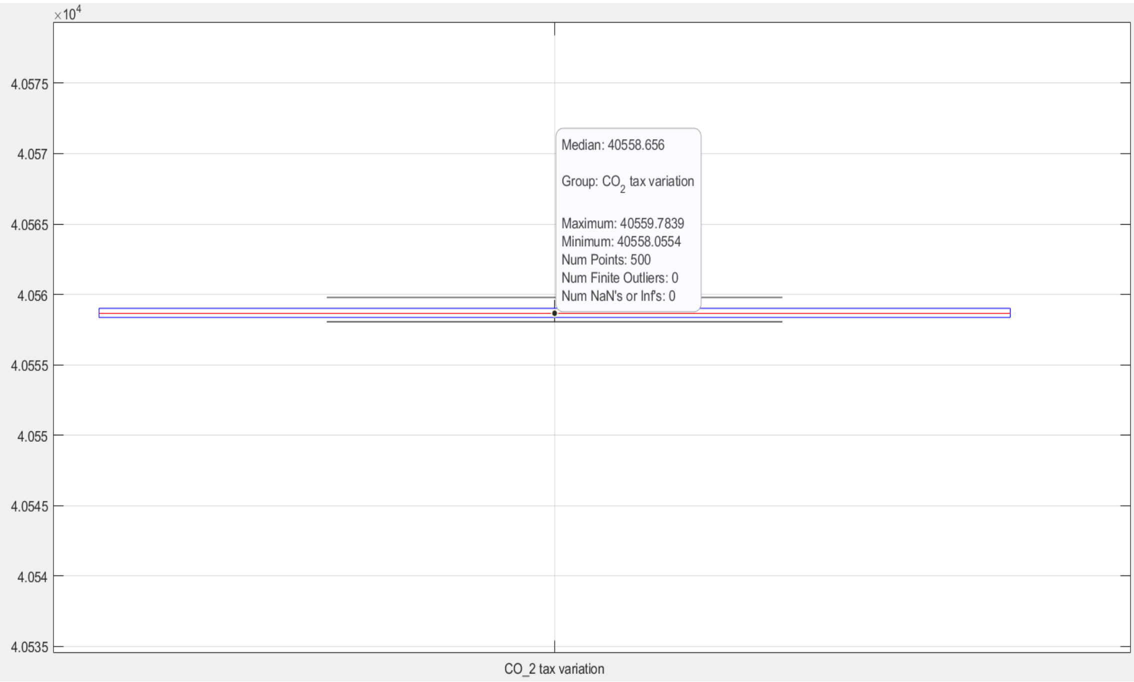

Figure 15. *Box Plot of CO2 Tax Variation.*

PV Invest Cost Variation

The figure provides an expanded view of the variation in the total annual cost resulting from changes in the investment cost of PV panels. The presence of a large box and long whiskers for the factor representing the investment cost variation suggests a higher level of volatility in annual costs compared to the other factors depicted by the remaining boxes. This implies that fluctuations in the investment cost of PV panels can exert a notable influence on the overall annual cost of the factory throughout the 20-year period.

Furthermore, an outlier value is evident within this specific factor, indicating a year in which the investment cost of photovoltaic panels significantly deviated from the average. This exceptional observation could be attributed to a range of factors, including shifts in the solar panel market dynamics, strategic decisions undertaken by the company, or distinct economic circumstances prevailing during that particular year.

It is essential to consider the implications of this outlier and its potential impact on the total annual cost. It may indicate a year of substantial investment in photovoltaic panels, leading to a higher cost but potentially resulting in greater energy generation and long-term savings. Alternatively, as it can be seen its value is 40223.86€, so it could represent a year of cost reduction in panel investment, potentially indicating efficiency improvements or favourable market conditions.

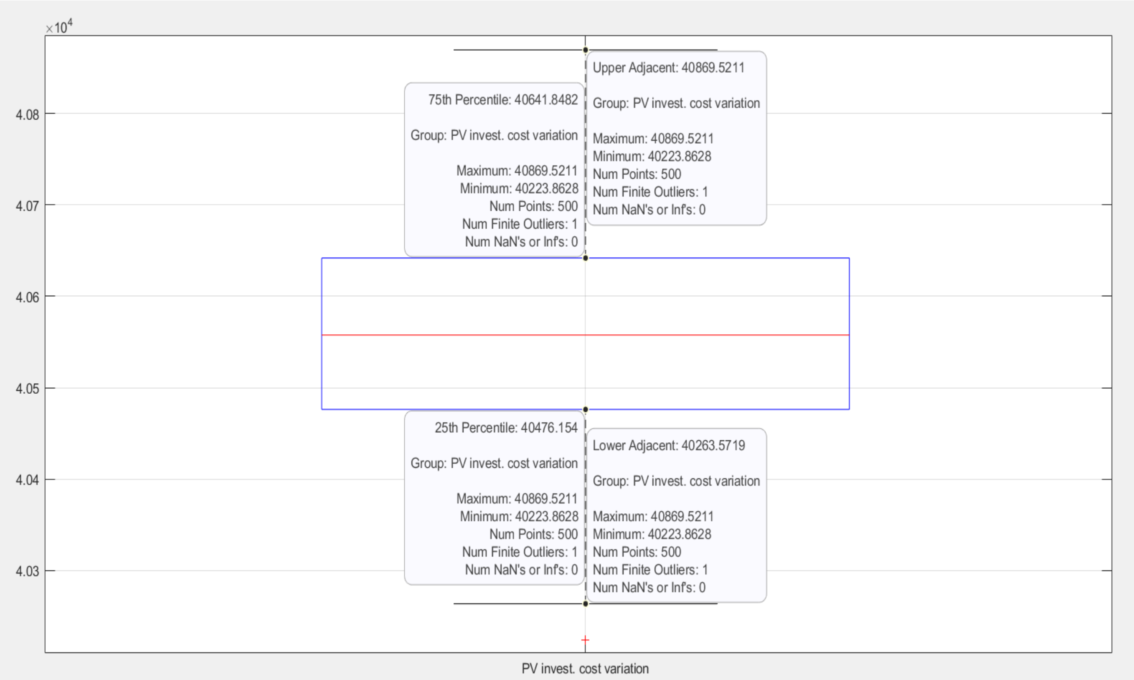

Figure 16. *PV Invest Cost Variation Box Plot.*

BESS Invest Cost Variation

In this specific scenario, the BESS invest cost variation box plot is shown. It is the second largest box in the box plot, both in terms of its size and the length of its whiskers, represents the variation in the investment cost of the BESS. The presence of a large box indicates a higher degree of variability in the annual costs associated with this factor compared to the other factors represented by the remaining boxes. This suggests that changes in the investment cost of the BESS can have a significant impact on the overall annual cost of the factory throughout the 20-year period.

Moreover, it is worth noting that there are three outlier values within this box. These outliers represent years in which the investment cost of the energy storage system deviated significantly from the other years. Such deviations could be attributed to various factors, including technological advancements in storage systems, fluctuations in equipment prices, or strategic decisions made by the company regarding the energy storage infrastructure. This is quite a success since the future and development of BESS technologies presents some uncertainty, as expressed in the distribution functions.

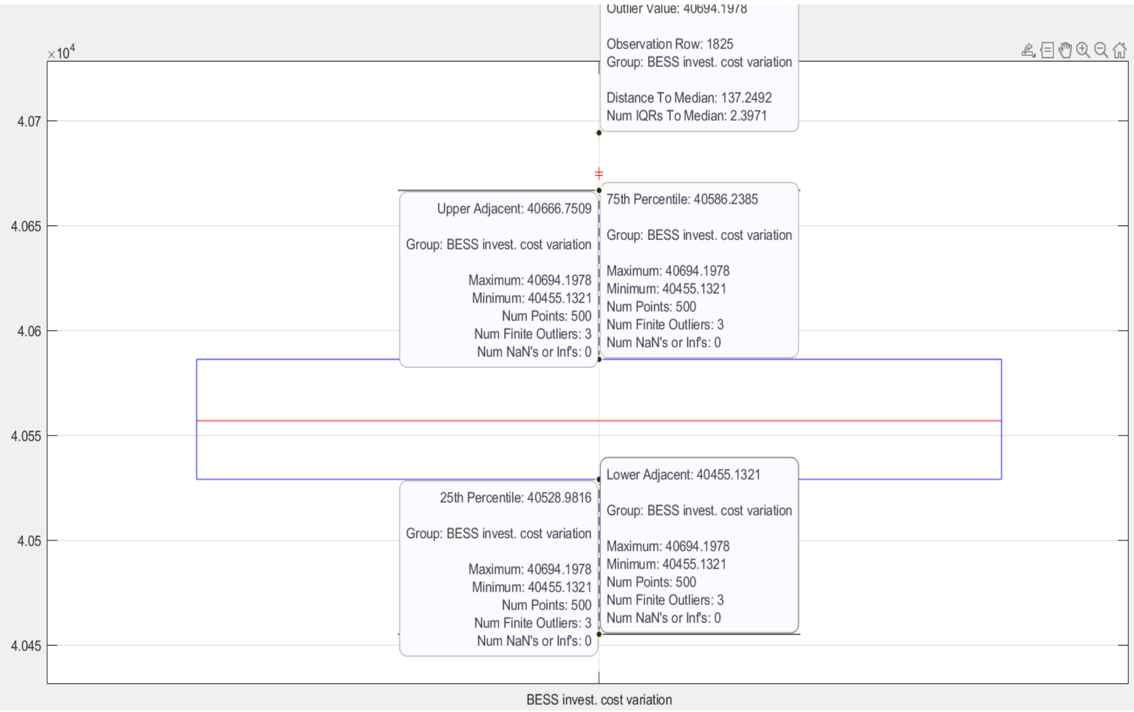

Figure 17. *BESS Invest Cost Variation.*

EVs Invest Cost Variation

Figure 18 shows the expansion of the graph where the variation of the annual cost caused by the variation in the investment of electric vehicles is analysed. Among the boxes, is the third largest one in terms of size. The size of this box, both in terms of the box itself and the whiskers, suggests that there is relatively higher variability in the annual costs associated with this factor compared to the other factors represented by the smaller boxes. This implies that changes in the investment cost of electric vehicles can have a notable impact on the overall annual cost of the factory over the 20-year period.

Furthermore, within this box, there are four outliers, three of which are located above the box and one below it. These above outliers indicate specific years in which the investment cost in electric vehicles deviated significantly from the other years. The presence of these outliers could be attributed to various factors, such as technological advancements in electric vehicles, fluctuations in vehicle prices, or strategic decisions made regarding the acquisition of electric vehicles.

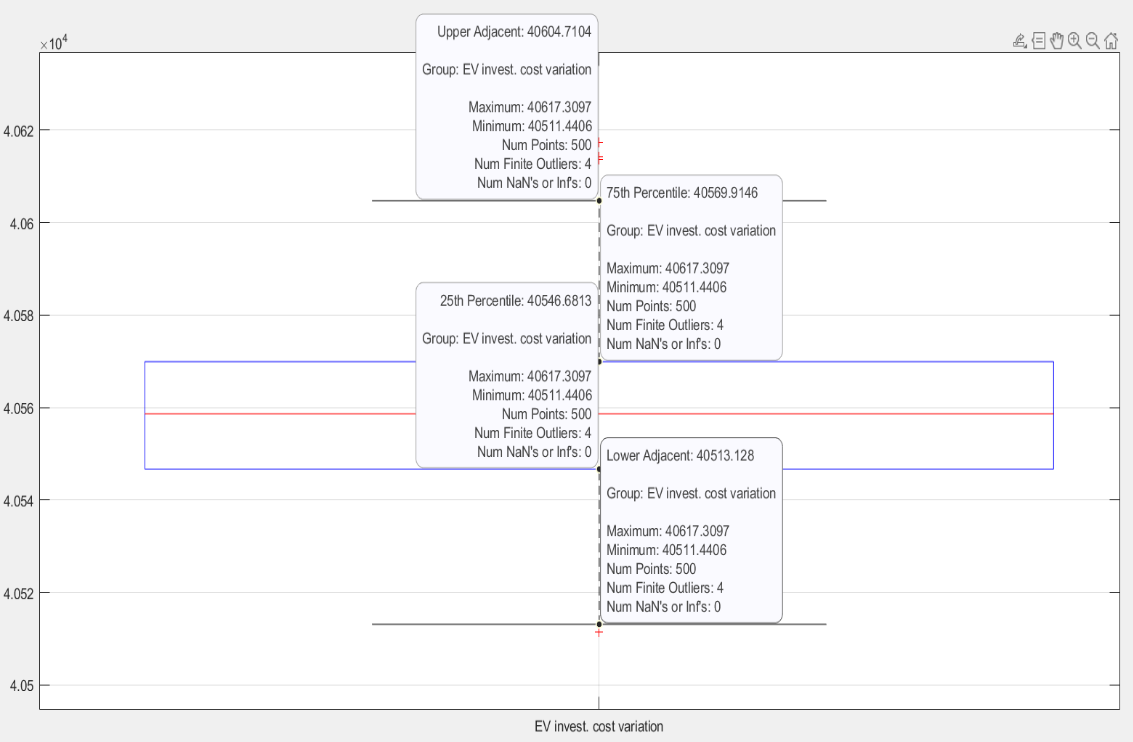

Figure 18. *EVs Cost Variation Box Plot.*

1.2. Annual CO2 Production

The following box plot, **Figure 13**, made in MATLAB represents the result of the annual production of CO2 expressed in the three components that can suppose a variation in its result: the grid carbon intensity, the PV carbon intensity and the battery carbon intensity.

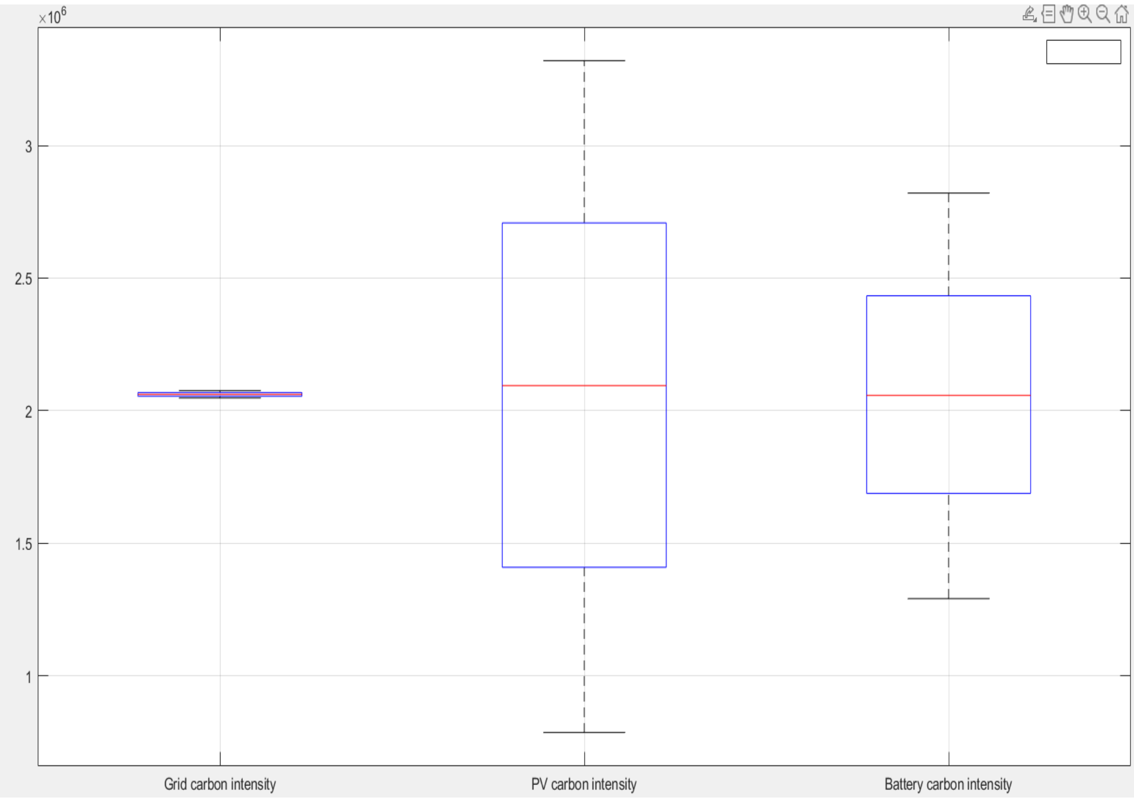

Figure 19. *Annual CO2 Production Box Plot.*

The median value of each component is shown in the **Table 4**. As can be seen, the value is practically the same with the variation of the three components of 2.072 tCO2 per year.

In addition, the annual CO2 production of 2.072 tCO2 per year for the net zero energy factory is considered remarkably low when compared to the CO2 emissions of conventional factories. This indicates that the NZEF has been successful in significantly reducing its carbon footprint and is making significant progress towards its goal of achieving zero emissions.

Looking at **Figure 19**, at first glance the median of the boxes of the three components is practically the same and remains constant. In a box plot representing the annual CO2 production of a factory acting as a NZEF over a 20-year period, the fact that the three boxes have the same median indicates that each factor represented by the boxes contributes equally to the variation in CO2 production. The median is the middle value that divides the data set into two equal parts.

The uniformity of the medians suggests that the three factors have a similar impact on the annual CO2 production. There is no dominant factor that has a significantly greater or lesser effect on emissions compared to the others. This implies that addressing each of these factors equally is crucial for achieving effective CO2 reduction throughout the analysed period.

This insight helps in understanding the composition of CO2 emissions from the factory and highlights the need to address all three factors in a balanced manner. By giving equal attention to each factor, the factory can effectively mitigate CO2 emissions and work towards achieving its NZEF goal.

Components of the Annual CO2 Production	**Median**	**[Units]**
Grid Carbon Intensity	2.062	tCO2/year
PV Carbon Intensity	2.095	tCO2/year
Battery Carbon Intensity	2.058	tCO2/year
Mean Value	2.072	tCO2/year

Table 4. *Median Values of the Components of the Annual CO2 Production.*

When examining each component individually, it is evident that they exhibit different sizes. The box plot reveals that one of the components is represented by a very small box and short whiskers, while the other two components are represented by larger boxes and longer whiskers. This discrepancy in size indicates that the component with the smaller box and whiskers has less variability in annual CO2 production compared to the other two components.

The smaller box and shorter whiskers suggest that this factor has a more consistent and predictable impact on CO2 production over the 20-year period, without experiencing significant fluctuations. On the other hand, the components with larger boxes and whiskers indicate greater variability and a potential for larger fluctuations in annual CO2 production.

By presenting the data in this manner, the box plot allows for a comparative analysis of the variability between the different components. It provides insights into the relative stability or volatility of each factor's influence on CO2 production.

Further discussion and analysis can now focus on each component individually to understand their specific characteristics and implications in the context of CO2 emissions from the factory.

Grid Carbon Intensity Variation

As previously introduced and as can be seen in **Figure 20**, the graphical representation of the variation of the Grid Carbon Intensity over the annual CO2 production is a very small box-and-whisker graph, both its box and its whisker.

Furthermore, knowing that this small size predicts a less fluctuant and more predictable profile, this suggests that the factory has successfully achieved a more stable and controlled Grid Carbon Intensity over the 20-year period. The small box and short whiskers in the box plot reflect a narrower range of CO2 production variations attributed to the Grid Carbon Intensity factor, compared to the larger boxes representing the other two factors.

The factory's ability to maintain a consistent Grid Carbon Intensity can be indicative of effective strategies and measures implemented to source cleaner and more renewable energy. By reducing the reliance on fossil fuels and transitioning to greener energy sources the factory has minimized the fluctuations in its CO2 production associated with electricity consumption. This demonstrates the factory's commitment to sustainable practices and its contribution to mitigating climate change. Additionally, the stable Grid Carbon Intensity allows for better planning and management of CO2 emissions, facilitating the factory's progress towards achieving its NZEF goal.

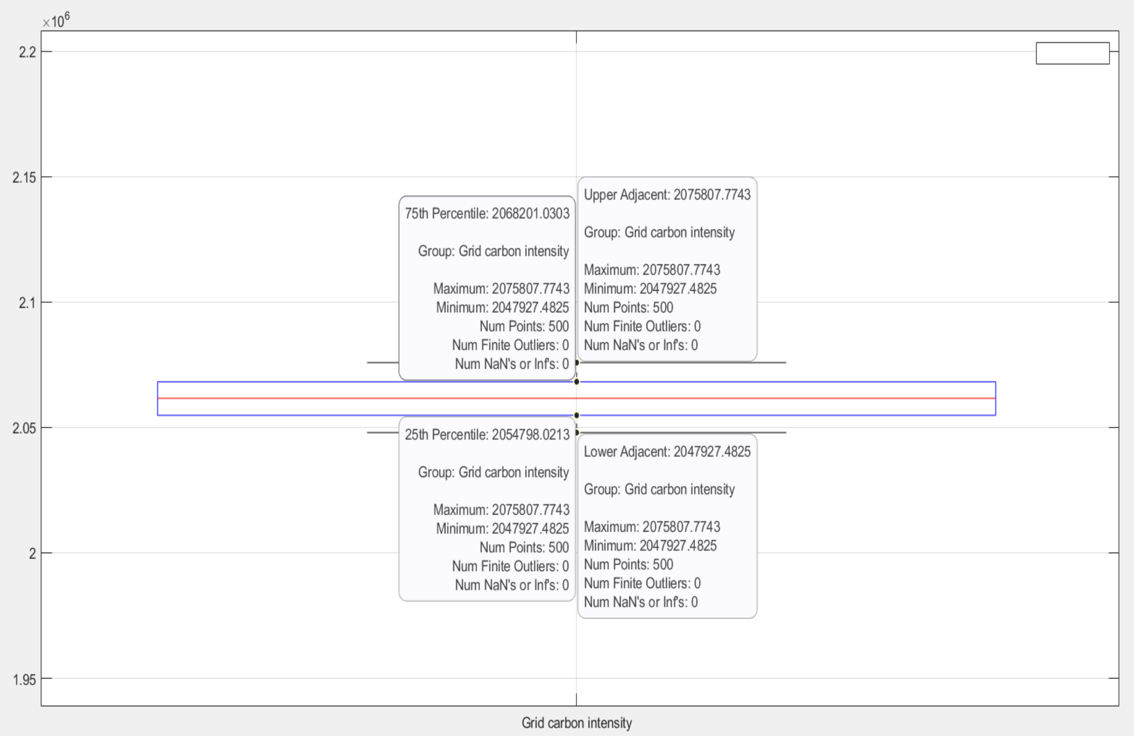

Figure 20. *Grid Carbon Intensity Variation Box Plot.*

PV Carbon Intensity Variation

Figure 21 shows the enlarged graph where the variation of the PV Carbon Intensity is represented in the calculation of the annual CO2 production.

The larger box and whiskers in the box plot representing the Carbon Intensity of PV panels suggest that this factor exhibits greater variability in annual CO2 production compared to the other two factors represented by smaller boxes.

This indicates that the Carbon Intensity of PV panels can have a significant and varying impact on the factory's CO2 production throughout the 20-year period. The variability in CO2 production may be influenced by factors such as the efficiency of the PV panels, the factory's geographic location, and local climatic conditions that affect solar energy generation. It should also be noted that in the factory, acting as NZEF, all the energy is produced through the PV panels, therefore it is logical that it is the parameter subject to the greatest fluctuation.

The larger box and whiskers also imply that there are more substantial fluctuations in the carbon intensity of PV panels over time. This could be attributed to changes in solar panel technology, fluctuations in equipment prices, or strategic decisions made by the factory regarding the use of PV panels.

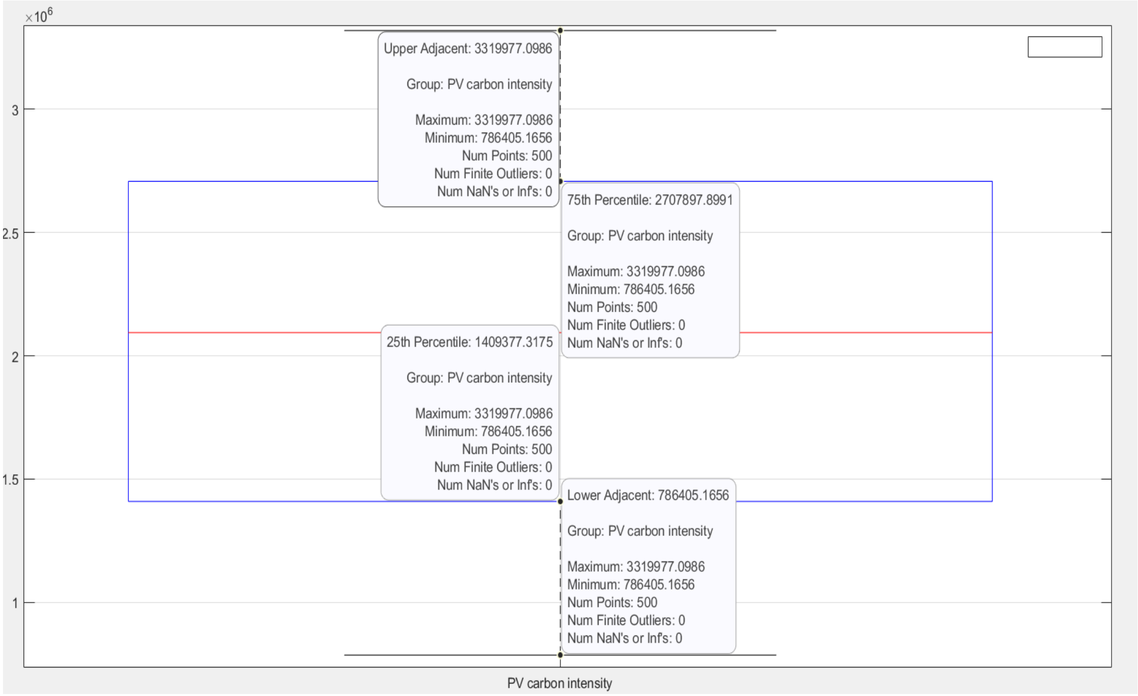

Figure 21. *PV Carbon Intensity Variation Box Plot.*

Battery Carbon Intensity Variation

Finally, **Figure 22** provides a closer look at the variation of the Battery Carbon Intensity in relation to the calculation of annual CO2 production. The graph shows that the box and whiskers for this parameter are the second largest, with the PV Carbon Intensity graph being the largest, as previously analysed. This indicates that the Battery Carbon Intensity can have a significant and variable impact on the factory's CO2 emissions throughout the 20-year period. The variability in CO2 production can be influenced by factors such as the efficiency of the batteries, the technologies employed for energy storage, and the management of energy charging and discharging.

Since battery technology is relatively recent and still evolving, it is expected to undergo more changes, as reflected in the distribution functions explained at methodology’s chapter. Therefore, it is logical to observe fluctuations in CO2 production associated with the carbon intensity of batteries. The larger box and whiskers also suggest that there may be more pronounced fluctuations in the carbon intensity of batteries over time. These fluctuations could be attributed to advancements in battery technology, shifts in market dynamics affecting battery prices, or strategic decisions made by the factory regarding the selection and utilization of batteries.

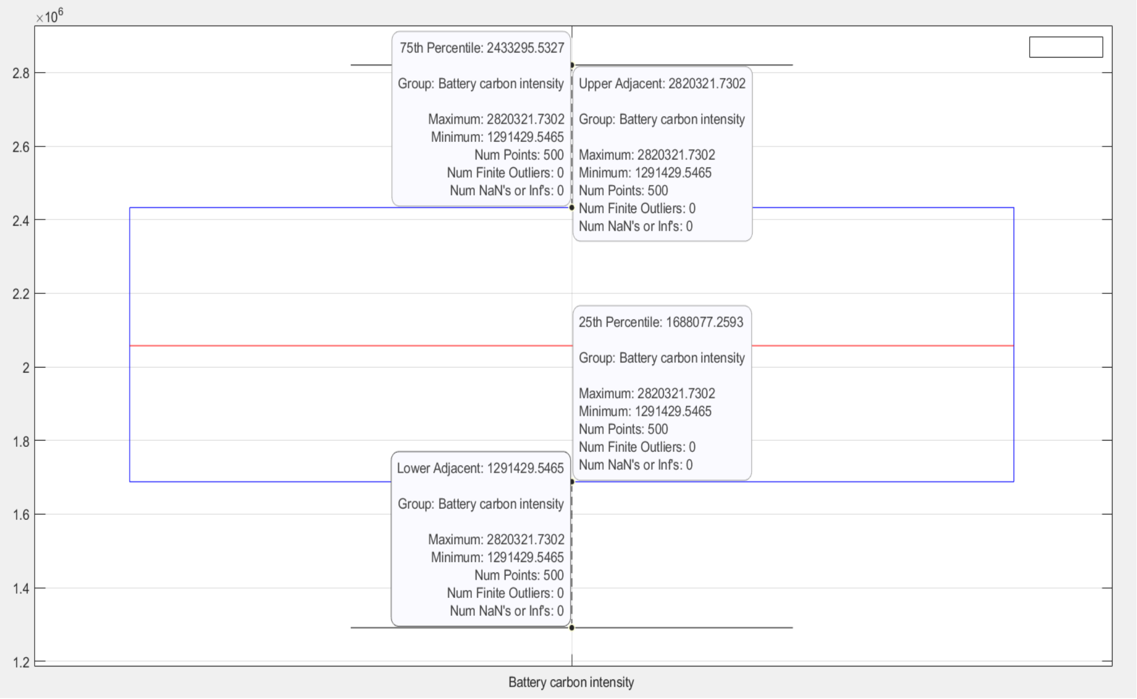

Figure 22. *Battery Carbon Intensity Variation Box Plot.*

Chapter 5: Conclusions

The primary aim of this thesis has been to conduct a technoeconomic analysis of a carpentry functioning as a Net Zero Energy Factory (NZEF) using a stochastic approach. By undertaking this study, the thesis aims to address two main objectives. Firstly, from a consumer's perspective, it seeks to proactively address and tackle the uncertainties associated with various scenarios that the factory may encounter. Secondly, from the standpoint of renewable energy sources, the goal is to minimize fluctuations and establish a reliable energy supply for the factory, ultimately enabling it to achieve self-consumption.

These objectives have been the focus in the trajectory of the study. Thanks to a detailed analysis of the external factors that significantly influence the factory and its corresponding approximation, through the exposed methodology, it has been possible to analyse the real data provided by the carpentry and significant results have been obtained.

By examining the interplay between the factory and its surrounding environment, as well as considering the various operational and economic factors, a comprehensive understanding of the carpentry's energy consumption patterns and potential areas for improvement has been attained. The incorporation of real data into the study has further enhanced the reliability and applicability of the findings, allowing for a more accurate evaluation of the carpentry's energy performance and its transition towards becoming a NZEF.

By calculating two main parameters, the total annual energy cost and the total annual production of CO2, some values stand out within the expected ranges. By representing the results, a correct distribution can be observed, making it a reliable and significant output.

A consumption of about €40,557.98 per year, which is acceptable with the factory's energy system model, and a production of 2,072 tons of CO2 per year, which is a very low and positive value. Some components of the calculation parameters present fluctuations which need to be considered in the long term, but still, both remain constant, which implies considerable reliability and stability in the application of the NZEF concept in the factory.

This reaffirms recent studies where the application of the NZEF concept represents a positive decision for companies, where the uncertainty and fluctuation of the RES is not a problem compared to the benefits it provides.

Thanks to these findings, a broad time horizon can be explored where long-term investments are an option, especially in renewable energies, thus not having to resort to the stability provided by conventional sources of energy generation up to now.

This is a recent field for which there are still not many references to real applications, therefore for future research it would be interesting to study the application of this analysis to factories located in any location, thus being able to create a standard NZEF model. By combining theoretical frameworks, practical insights, and empirical evidence, this study has contributed to the body of knowledge in the field of net zero energy factories. The findings provide valuable guidance for policymakers, energy planners, and stakeholders seeking to implement sustainable energy practices in industrial sectors.

This thesis has led me to the discovery of a new field of application of renewable energies as well as the characterization of uncertain factors and most importantly, the replacement of conventional energy sources thanks to a long-term reliability profile of renewable energies.

Bibliography

[1] E. A. Strategy, “EU Adaptation Strategy,” [Online]. Available: EU Adaptation Strategy (europa.eu). [Accessed 10 5 2023].

[2] E. P. Climate action in Italy, “Europarl.europa.eu,” [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/690663/EPRS_BRI(2021)690663_EN.pdf. [Accessed 20 5 2023].

[3] L.-t.-t. e. s. t. e. t. i. y. o. home, “Federal Ministry for Economic Affairs and Climate Action,” [Online]. Available: https://www.bmwk.de/Redaktion/EN/Artikel/Energy/landlord-to-tenant-electricity-supply.html. [Accessed 20 5 2023].

[4] P. Lombardi and M. Liserre, “Net-zero energy factory: Exploitation of flexibility –A technical-economic analysis for a German,” 2020.

[5] P. Lombardi, B. Arendarskie, P. Komarnicki, M. Santarelli, A. M. Pantaleo and M. Liserre, “Exploitation of Flexibility within Net-zero Energy Factories. A Study Case for a German Carpentry Works,” 2021.

[6] A. Ahmed , T. Ge, J. Peng, W.-C. Yan , B. Tuan Tee and S. You, “Assessment of the renewable energy generation towards net-zero energy buildings: A review,” 2022. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0378778821010392?casa_token=woiV_U5itV4AAAAA:uqg9ExRmakyLAattApjZt_cLFZiVyjKIQT0T-vwWFuHAsqkprWWP3UzX399PxD-SYljftsVW. [Accessed 20 5 2023].

[7] I. Sartori , A. Napolitano and . K. Voss, “Net zero energy buildings: A consistent definition framework,” 2012. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0378778812000497. [Accessed 20 5 2023].

[8] E. Musall, T. Weiss, K. Voss, A. Lenoir, M. Donn, S. Cory and F. Garde, “Net

Zero Energy Solar Buildings: An Overview and Analysis on Worldwide Building Projects," [Online]. Available: https://w.iea-shc.org/Data/Sites/1/publications/STC134895.pdf. [Accessed 20 5 2023].

[9] W. Wu and H. M. Skye, "Residential net-zero energy buildings: Review and perspective," 2021. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1364032121001532. [Accessed 20 5 2023].

[10] "Tesla Gigafactory Nevada," [Online]. Available: https://www.tesla.com/giga-nevada. [Accessed 20 5 2023].

[11] "Mitsubishi Electric Facility Receives Net Zero Energy Building Certification," [Online]. Available: https://www.mitsubishielectric.com/news/2019/0807.html. [Accessed 5 20 2023].

[12] "German Federal Ministry for economic affairs and energy. Renewable Energy Sources," [Online]. Available: https://www.bmwk.de/Redaktion/DE/Downloads/G/gesetzentwurfaenderung-erneuerbare-energien-gesetzes-und-weitererenergierechtlicher-vorschriften.pdf?__blob=publicationFile. [Accessed 20 5 2023].

[13] L. Bartolucci, S. Cordiner, V. Mulone and C. Tatangelo, "Assessment of Hybrid Commercial Fleet Performance: Effects of Advanced Control Strategies for Different Geographical Sites," 2022.

[14] L. Bartolucci, "Hydrogen Fuel Cell Hybrid Electric Vehicles: the," 2022.

[15] G. Mavromatidis, K. Orehounig and J. Carmeliet, "Uncertainty and global sensitivity analysis for the optimal design of distributed energy systems," [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0306261918300710?via%3Dihub. [Accessed 2 6 2023].

[16] S. Burhenne, O. Tsvetkova, . D. Jacob and G. P. Henze, "Uncertainty quantification for combined building performance and cost-benefit analyses,"

[Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0360132313000280?via%3Dihub. [Accessed 2 6 2023].

[17] P. CALANTER and D. ZISU, “EU Policies to Combat the Energy Crisis,” [Online]. Available: http://www.globeco.ro/wp-content/uploads/vol/split/vol_10_no_1/geo_2022_vol10_no1_art_003.pdf. [Accessed 2 6 2023].

[18] G. Garyfallos, I. P. Athanasios, S. Panos and V. Spyros, “Optimum design and operation under uncertainty of power systems using renewable energy sources and hydrogen storage,” [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0360319909018138?via%3Dihub. [Accessed 2 6 2023].

[19] C. Howard, “Distributions for Uncertainty Analysis,” [Online]. Available: http://www.isgmax.com/Articles_Papers/Distributions%20for%20Uncertainty%20Analysis%20-%20Revised.pdf. [Accessed 2 6 2023].

[20] M. S. Stephen, “The History of Statistics: The Measurement of Uncertainty Before 1900. Harvard University Press,” 1986. [Online]. Available: https://books.google.ch/books?id=M7yvkERHIIMC. [Accessed 2 6 2023].

[21] K. B. Kurt, E. L. Kim and J. H. Andrew, “Parameter uncertainty, sensitivity analysis and prediction error in a water-balance hydrological model,” [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0895717707002373. [Accessed 2 6 2023].

[22] Eurostat, “Eurostat Data Browser,” [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/NRG_PC_205/default/table?lang=en&category=nrg.nrg_price.nrg_pc. [Accessed 4 6 2023].

[23] M. Georgios, O. Kristina and C. Jan, “A review of uncertainty characterisation approaches for the optimal design of distributed energy systems,” [Online]. Available:

https://www.sciencedirect.com/science/article/abs/pii/S1364032118300510?via%3Dihub. [Accessed 4 6 2023].

[24] T. Couture and Y. Gagnon, “An analysis of feed-in tariff remuneration models: Implications for renewable energy investment,” 2010. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0301421509007940. [Accessed 4 6 2023].

[25] B. Bakhtyar, A. Fudholi, K. Hassan, M. Azam, C. Lim, N. Chan and K. Sopian, “Review of CO2 price in Europe using feed-in tariff rates,” 2017. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S136403211630911X?via%3Dihub. [Accessed 4 6 2023].

[26] P. Magazine, “Feed-in tariffs (FITs) in Europe,” [Online]. Available: https://www.pv-magazine.com/features/archive/solar-incentives-and-fits/feed-in-tariffs-in-europe/#germany. [Accessed 4 6 2023].

[27] “Organisation for Economic Co-Operation and Development,” [Online]. Available: https://stats.oecd.org/Index.aspx?DataSetCode=RE_FIT. [Accessed 4 6 2023].

[28] B. Lin and X. Li, “The effect of carbon tax on per capita CO2 emissions,” [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0301421511004502?casa_token=-oBgzz_X8o0AAAAA:189twP0nXy8tm4ytks_ObMl7TyGRoRrr-wC2hlcZ9RIrNlQfDTmDSMS4QMjoru8Q8BEZ3p19. [Accessed 4 6 2023].

[29] E. E. Bureau, “Designing an ambitious and socially fair carbon pricing,” [Online]. Available: https://eeb.org/wp-content/uploads/2022/03/German-Emissions-Trading-System-for-buildings-and-transport.pdf. [Accessed 4 6 2023].

[30] C. E. Wire, “CO2 pricing brings Germany record 13 billion euros in revenues in 2022,” 2023. [Online]. Available: https://eeb.org/wp-

content/uploads/2022/03/German-Emissions-Trading-System-for-buildings-and-transport.pdf. [Accessed 4 6 2023].

[31] D. García-Gusano, K. Espegren, A. Lind and M. Kirkengen, “The role of the discount rates in energy systems optimisation models,” 2016. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S1364032116000253?casa_token=1ArhXweSZJEAAAAA:7QcvSbGQb-BAFzJmT666KXGEtRQ1ZljpGnxucmfk7-JbNNCq7XcwRHEo1BldFdjeDP1K4bpb. [Accessed 4 6 2023].

[32] “RE Frame,” [Online]. Available: http://re-frame.eu/. [Accessed 4 6 2023].

[33] Oxera, “The role of the discount rates in energy systems optimisation models,” 2011. [Online]. Available: https://www.oxera.com/wp-content/uploads/2018/03/Oxera-report-on-low-carbon-discount-rates.pdf. [Accessed 10 6 2023].

[34] A. Moro and L. Lonza, “Electricity carbon intensity in European Member States: Impacts on GHG emissions of electric vehicles,” 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920916307933?via%3Dihub. [Accessed 10 6 2023].

[35] I. Petkov and P. Gabrielli, “Power-to-hydrogen as seasonal energy storage: an uncertainty analysis for optimal design of low-carbon multi-energy systems,” 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1361920916307933?via%3Dihub. [Accessed 10 6 2023].

[36] S. L. Center, “What is the Carbon Footprint of Solar Panels?,” 2023. [Online]. Available: https://www.solar.com/learn/what-is-the-carbon-footprint-of-solar-panels/#:~:text=There%20have%20been%20many%20studies,kilowatt%20hour%20of%20electricity%20produced. [Accessed 10 6 2023].

[37] E. Comission, “Environmental Footprint methods,” [Online]. Available: https://green-business.ec.europa.eu/environmental-footprint-methods_en. [Accessed 10 6 2023].

[38] N. R. E. Laboratory, “Best Practices for Operation and Maintenance of Photovoltaic and Energy Storage Systems,” 2018. [Online]. Available: https://www.nrel.gov/docs/fy19osti/73822.pdf.

[39] P. Lombardi, S. Yadav Mattepu, B. Arendarski, M. Richter and P. Komarnicki, “Blockchain application within Net-Zero Energy Factories. A cost-benefit analysis for a German Carpentry”.

[40] M. Kaut, K. T. Midthun, A. S. Werner, A. Tomasgard, L. Hellemo and M. Fodstad, “Multi-horizon stochastic programming,” 2014.

[41] M. Robati, D. Daly and G. Kokogiannakis, “A method of uncertainty analysis for whole-life embodied carbon emissions (CO2-e) of building materials of a net-zero energy building in Australia,” 2019. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0959652619310558?casa_token=GnS3zcmtv8sAAAAA:wf42Dhpo0W_ONLdKgxFLgTVhSHl1j9jr5dPaab9ozGPNz4C6ivyEFmjnz7r0gftFPM-ghT4G. [Accessed 15 6 2023].

[42] S. Burhenne, O. Tsvetkova, D. Jacob, G. P. Henze and A. Wagner, “Uncertainty quantification for combined building performance and cost-benefit analyses,” 2013. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0360132313000280?via%3Dihub. [Accessed 15 6 2023].

[43] V. Becattini, P. Gabrielli and M. Mazzotti, “Role of Carbon Capture, Storage, and Utilization to Enable a Net-Zero-CO2-Emissions Aviation Sector,” 202. [Online]. Available: https://pubs.acs.org/doi/full/10.1021/acs.iecr.0c05392. [Accessed 15 6 2023].

[44] P. Lombardi, C. Wenge and R. Pietracho , “Multi Usage Applications of Li-Ion Battery Storage in a Large Photovoltaic Plant: A Practical Experience,” 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/18/4590.

[Accessed 15 6 2023].

[45] M. Mathworks. [Online]. Available: https://es.mathworks.com/help/matlab/ref/boxchart.html. [Accessed 30 6 2023].