Master Thesis

Master's degree in Energy Engineering

Power System Modelling

A techno-economic analysis of the island of Menorca, Spain

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Summary

It is hard to overstate the need for humanity to address what is arguably one of the most pressing issues of our generation: climate change. Although electricity generation only accounts for about a quarter of global carbon emissions, it is one of the sectors for which a wide range of technologies are already commercially available and increasingly competitive. The decarbonization of other energy-intensive and high emitting sectors: agriculture, transportation, heating and industrial processes such as cement and steel production, although still lagging behind due to both technical and economic challenges, are beginning to show signs of progress. In some cases, electrification will be the most viable path to decarbonization, as seen in the light-duty transportation sector, where electric vehicles are already a reality. For many others, technological innovation will play a crucial role in bringing viable solutions to market. If approached pragmatically, the power sector is in a position to be the first piece of the puzzle to transition to a fundamentally sustainable way of sourcing energy.

The analysis herein presented aims to identify the cost-optimum power system that can reliably supply the Spanish island of Menorca with electricity for the next ten years, from 2021 to 2030. Menorca's power sector is computationally modelled and simulated using the open-source power system modelling tool *Switch 2.0*. The study is divided into different scenarios and the results of the techno-economic optimization are presented and discussed in terms of their technical feasibility, carbon footprint and costs. In addition to a standard base case scenario, the impact of factors such as fuel cost fluctuations and policy-related externalities (carbon price and renewable energy mandates) are also assessed as separate scenarios.

The results of the techno-economic analysis show a clear and consistent trend across all scenarios: renewable energy technologies, namely solar PV and onshore wind power, represent the cheapest source of new bulk electricity generation in Menorca. As such, they are poised to drastically change the current fossil-based and centralized power system of the island, becoming the main sources of electricity. The base case – the most conservative scenario, in which carbon emissions are not priced, fuel costs are kept constant and no renewable energy mandate is set – solar PV and wind power account for two thirds of the total electricity supply by 2030. The penetration of renewables is even higher for the other scenarios modelled.

The viable integration of such high levels of intermittent renewable energy is highly dependent on the flexibility offered by dispatchable and controllable power generation assets. A cost-optimum system for Menorca relies on two main technologies for such purposes: transmission via the existing submarine interconnection to Mallorca and natural gas turbines. The Mallorca-Menorca sea-cable is responsible for about a quarter of the total electricity supply by 2030 for scenarios without a renewable mandate, the biggest share after solar and wind.

Open cycle natural gas turbines complement the system, mainly supplying power during the evening peaks and in the summer months when demand almost doubles due to higher temperatures and a big influx of tourists in the island. This complementary role represents the bulk of the remaining supply of electricity, about 8% by 2030. Despite their relatively low share of total generation, the operational flexibility and fast ramping capabilities of open cycle natural gas turbines offer the electrical network a series of benefits, from ancillary services essential for grid stability to spinning reserves for the integration of high levels of intermittent renewables.

Lithium-ion batteries, the only storage mechanism considered, play a marginal role in a cost-optimized power system for Menorca in the next ten years. Though modelled with the steepest cost reduction curve of all technologies, a 48% drop in prices by 2030, batteries are only competitive for a very specific use-case: short-term shift of renewable energy to meet the evening peak in demand, which usually occurs between 17:00 and 19:00 when solar generation quickly drops as the sun sets. The only scenarios in which batteries take a higher than 1% share of total electricity supply are the ones in which a renewable portfolio standard (RPS) is imposed. To ensure compliance with the 2030 RPS targets simulated, the sea-cable and natural gas participations are displaced by a combination of additional solar PV and wind power coupled with batteries that can store and shift excess renewable generation to match intraday demand.

The economic competitiveness of solar PV and wind power have a significant impact on the carbon footprint of Menorca's electrical grid. Over the next ten years, the lowest-cost power system identified for each of the scenarios modelled shows a reduction of at least 85% in carbon emissions relative to 2019 levels. This drastic impact is in part due to the high carbon intensity of Menorca's current power system, which relies mostly on diesel and fuel-oil generators. Nevertheless, it also highlights a clear path for the island to improve the efficiency of its grid, all the while making electricity cheaper, cleaner and more sustainable.

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Glossary

BNEF	Bloomberg New Energy Finance
BOS	Balance of system
CAPEX	Capital expenditure
CCGT	Combined cycle gas turbine
CCS	Carbon capture and storage
CIME	Consell Insular de Menorca (Insular Council of Menorca)
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conference of Parties (UNFCCC)
CSP	Concentrated solar power
DSM	Demand side management
EC	European Commission
EEA	European Environment Agency
EIA	Energy Information Administration (United States)
EPA	Environmental Protection Agency (United States)
ESIOS	Sistema de Información del Operador del Sistema
ETS	Emissions Trading System (European Union)
EU	European Union
EUR	Euro currency (€)
EV	Electric vehicle
gCO2-eq	Grams of CO_2 equivalent
GDP	Gross domestic product
GESA	Gas y Electricidad Generación S.A.
GHG	Greenhouse gas
GOB	Govern Illes Balears (Government of the Balearic Islands)
GW	Gigawatt
GWh	Gigawatt-hour
GWP	Global warming potential
HFC	Hydrofluorocarbon
HRSG	Heat recovery steam generator
HVAC	High-voltage alternating-current
HVDC	High-voltage direct-current
IEA	International Energy Agency
IME	Institut Menorquí d'Estudis (Menorcan Institute of Studies)
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal rate of return (finance)

kV	Kilovolt
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
MIBEL	Mercado Ibérico de Electricidade
MIP	Mixed integer programming
MMBtu	Million British thermal units
MSW	Municipal solid waste
MW	Megawatt
MWh	Megawatt-hour
MWp	Megawatt-peak
NOx	Nitrogen oxides
NPV	Net present value (finance)
NREL	National Renewable Energy Laboratory (United States)
O&M	Operations and maintenance
OBSAM	Observatori Socioambiental de Menorca
OCGT	Open cycle gas turbine
OPEX	Operational expenditure
p.a.	Per annum
PFC	Perfluorocarbon
PHS	Pumped hydro storage
PM	Particulate matter
ppm	Parts per million
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information Systems
REE	Red Eléctrica de España (Spain's TSO)
RPS	Renewable portfolio standard
SNP	Sistemas no peninsulares (non-peninsular electrical systems)
SOx	Sulphur oxides
STC	Standard test conditions
TSO	Transmission system operator
TTF	Title transfer facility
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UPC	Universitat Politècnica de Catalunya
USD	United States dollar ($)
WHO	World Health Organization
YoY	Year-over-year (statistical comparison)

1. Preface

The study herein presented is motivated by the need for humanity to transition to a sustainable energy future. To avoid falling victim to the overwhelming size and difficulty of this proposition, we shall understand the problem from a top-down approach, looking at its scale and impact globally; but proposing to tackle it from a bottom-up perspective, by changing and adapting local systems that together make up all the energy uses of modern civilization[1].

More specifically, this study presents a techno-economic analysis of the power system of *Menorca*, a Spanish island located in the Mediterrenean Sea. Because islands present a series of special constraints and characteristics, their study can provide insightful results with findings that are often replicable and scalable.

1.1. Background

When looking back at – what our generation would deem – the simple and primitive life of our ancestors a few thousand years ago, the progress made by the human race is hardly believable. We have gone from hunter-gatherer communities spread across the world to an interconnected global species that is at the brink of interfacing with the digital world, which we ourselves created. Despite the countless improvements to living standards, made possible by technology and labor, much of it has come at the expense of the planet's homeostasis; the very planet that supplies all the resources to make such progress possible, not to mention life itself.

One of the most pressing environmental issues currently faced by humans is climate change, as it challenges us to alter the foundations on which modern civilization is built. In order to understand the climate crisis and contextualize the motivation behind this project, it is important to look at history and try to understand the root causes that lead to today's dire state of affairs.

1.1.1. The Industrial Revolution

More than two centuries ago, the Industrial Revolution put in motion a series of socioeconomic events that have become the foundational blocks of the modern world. In fact, the Industrial

[1] Throughout this report, the term *"modern civilization"* shall refer to the post industrial revolution age, all the way to the current year (2020).

Revolution is arguably still happening, albeit not in the form of steam engines pumping dirty smoke into the sky – the way most of us tend to picture it (Figure 1).

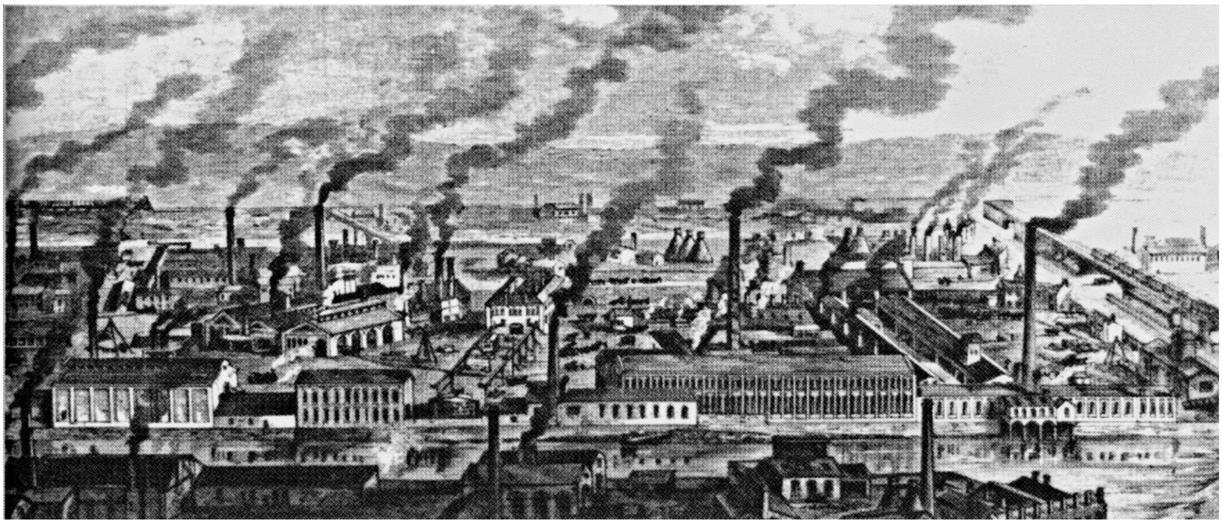

Figure 1 - A portrayal of the (first) Industrial Revolution [1]

Today, the term *Industrial Revolution* often refers to a sequence of technological discoveries and advances that have allowed for continuous socioeconomic and technological progress across several areas and sectors of our civilization. From the mass production of goods with the introduction of the assembly line and the global proliferation of electrical networks that power the world's factories and urban centers; to the use of silicon-based semiconductors in computer processors for the automation and digitization of the economy and the *World Wide Web*, a global network of interconnected telecommunication devices that allow the instantaneous flow of data and information across continents, known by most as the *Internet*.

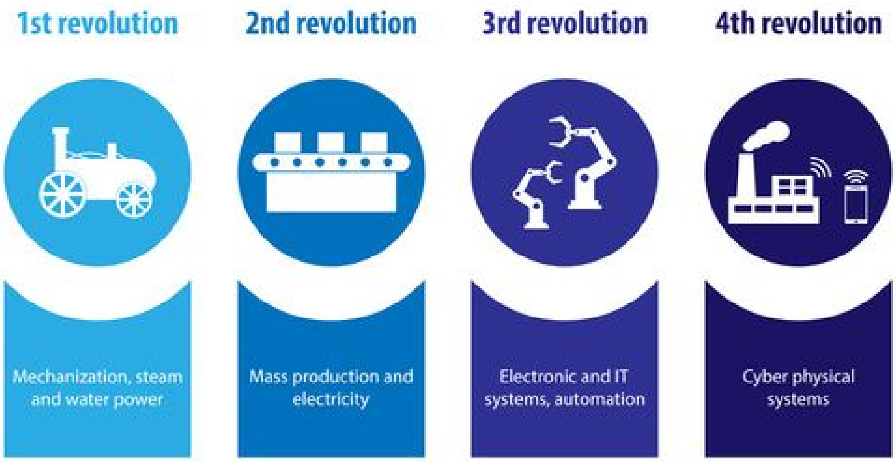

Figure 2 - The four phases of the Industrial Revolution leading up to today [2]

With such a comprehensive and encompassing interpretation, the Industrial Revolution can be divided into four different phases, based on the chronological advent of some key technologies (Figure 2). Based on this categorization, we are now living the *Industrial Revolution 4.0*, characterized by the increased integration of computers into the social fabric, with ever more connected and ubiquitous electronic devices that can interact with humans in a phenomenon called *Internet of Things (IoT)*, and the development of artificial intelligence, in an attempt to make machines more capable of solving complex non-uniform problems.

1.1.2. The natural environment

Despite the unquestionable technological progress of the last two and a half centuries, which have dramatically improved productivity, standards of living and life expectancy globally, the growing demand for the feedstocks needed to maintain the wheels of progress spinning has become unsustainable. Natural resources essential for life are being depleted and habitats irreversibly disrupted by the wasteful byproducts of human activity, which can no longer be absorbed by the planet without affecting its equilibrium.

It took the Earth about 4.5 billion years to achieve a finely tuned balance between fauna, flora and inorganic matter. Despite its exuberance and robustness, housing what scientists estimate to be billions of different species[2], the conditions needed for the maintenance of the planet's biosphere are a complex function of interconnected and cyclical phenomena, which can be disturbed by seemingly small external perturbations.

This dichotomy between socioeconomic progress and environmental sustainability is currently manifesting itself in what is arguably the biggest existential challenge ever faced by human kind: *climate change*. For much of the last two hundred years, hydrocarbons formed by the decomposition of fossilized organic molecules over millions of years have served as the elemental fuel (literally) for social development and economic growth. As a result, another type of revolution has now come overdue. It is one that requires cooperation at a global scale for the creation and deployment of technologies that can replace the very foundation of the world's fossil-based energy system with something that is both sustainable and carbon-free.

[2] Scientific estimates range from the order of a few millions [3] to as high as a trillion [4]. This incredibly wide range highlights how little we know about life on Earth.

1.2. Motivation

1.2.1. Climate change

Since the (first) Industrial Revolution, fossil fuels have been a crucial enabler for the advancement of human civilization. Coal, petroleum[3] and natural gas are currently the most widely used sources of energy. Their high energy density combined with a mature and efficient global supply chain – both upstream and downstream – have turned the fossil industry into an indispensable precursor to socioeconomic progress: from the production of combustible fuels that power generators and vehicles in the most remote corners of the world, to the vast array of petrochemicals[4] used to make plastics, medicines, cosmetics, rubbers, resins, synthetic fibers, adhesives, dyes, detergents and pesticides, among other products omnipresent in our daily lives.

Despite their flexibility and versatility, the incessant use of fossil fuels on a global scale and over so many decades, has resulted in some rather adverse effects on the natural environment. These effects derive not only from the extraction and exploration of fossil fuels buried under the ground – a process highly disruptive to local ecosystems – but mainly from their use as an energy source. The high amount of heat (i.e. energy) released when fossil fuels are burned have made them the undisputed preferred fuel across a multitude of sectors and applications. According to the International Energy Agency (IEA), the world's total final energy consumption in 2017 was around 113,000 terawatt-hours (406.8 billion gigajoules), of which more than three quarters (77%) came from burning coal, oil and natural gas [6].

Some of the byproducts of burning fossil fuels are greenhouse gases (GHGs), of which the most common one[5] is carbon dioxide (CO_2). As a result of the combustion reaction, GHGs are generally emitted into the Earth's atmosphere. In 2017, global energy-related emissions are estimated to have been 32.8 gigatonnes of CO_2-equivalent, a 60% increase over carbon emission levels in 1990 [7].

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[3] The words *petroleum* and *oil* shall be used interchangeably throughout this report.

[4] According to the IEA, the expected growth in demand for petrochemical products will result in petrochemicals accounting for over a third of the growth in oil demand by 2030, and nearly half by 2050; ahead of trucks, aviation and shipping [5].

[5] Other GHGs include: methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF3). GHG emissions are commonly normalized to CO_2-equivalent based on the global warming potential of each molecule.

It is important to note that greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) are naturally occurring substances that are also produced by activities not necessarily linked to fossil fuels, such as fires, agricultural practices and livestock (i.e. manure), among others. However, the scale at which the consumption of fossil fuels is taking place has resulted in a rapid increase in the amount of GHGs in both the atmosphere and the oceans[6]. The concentration of CO_2 in the atmosphere is currently at an all time high of 417 parts per million (ppm) as of May 2020 [9], while annual emissions are yet to peak (Figure 3).

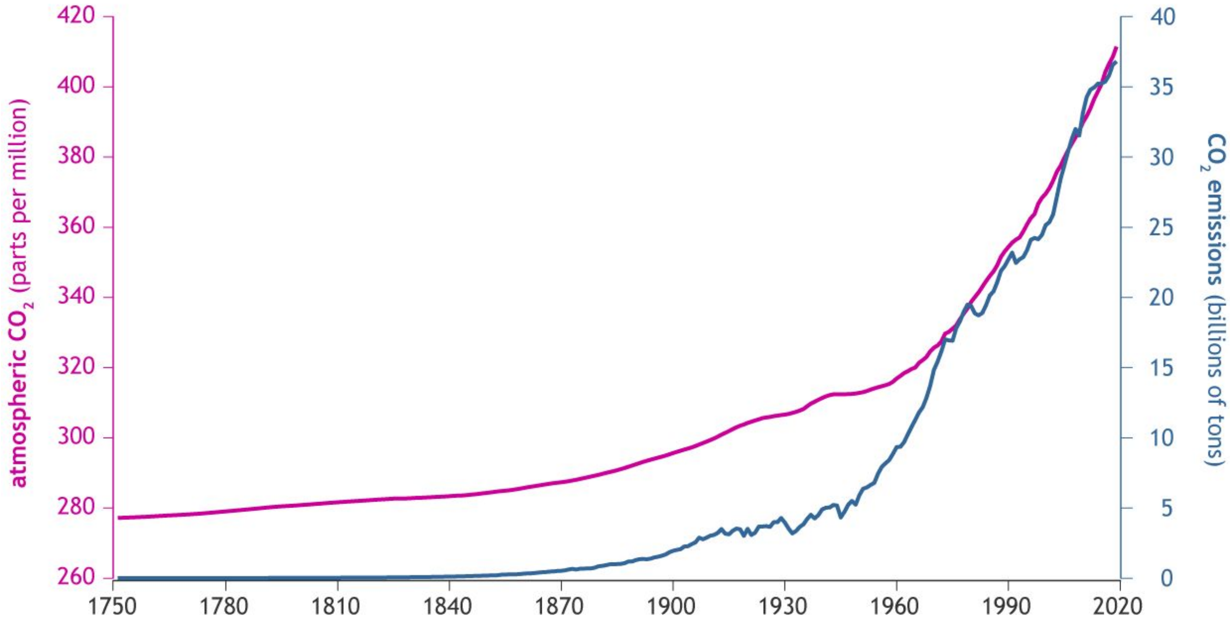

Figure 3 - CO_2 concentration in the atmosphere and annual emissions, 1750-2019 [10]
(Elaboration: NOAA Climate.gov)

As the name suggests, greenhouse gases in the Earth's atmosphere have heat-trapping properties (similar to the glass roof of a greenhouse). Although humans would likely not survive the low temperatures that would occur in the complete absence of any greenhouse effect in the atmosphere, the intensification of this phenomenon as a consequence of GHG emissions from human activity is causing changes to the climate that threaten the balance of the biosphere. Some of the predicted effects include changes in the behavior of ocean streams, more frequent extreme weather events (i.e. hurricanes, cyclones, droughts, floods, etc), an increase in the

[6] When carbon dioxide CO_2 is released into the atmosphere from the burning of fossil fuels, approximately 50% remains in the atmosphere, while 25% is absorbed by land plants and trees, and the other 25% is absorbed into certain areas of the ocean. In other areas of the ocean, where the concentration of CO_2 is higher in the water than in the atmosphere above, CO_2 is released to the atmosphere [8].

planet's temperatures and a consequent sea level rise due to the melting of the ice sheets and glaciers causing mass migration and extinction of living organisms,.

Despite the numerous efforts from the scientific community to try to understand and forecast the precise effects of human induced climate change, the intricate system of feedback loops that regulate the equilibrium of the Earth's ecosystems is likely to result in many unforeseen events, many of which we may not be equipped to deal with.

In an insatiable thirst to accelerate the progress of the last centuries, we, humans, seem to have lost track of the risks it poses to our future. A paradigm shift in the form of an energy revolution to drastically change the world's fossil-based and carbon-intensive energy system, to a clean and circular model is crucial to the existence of modern civilization as we know it, for ourselves and especially for future generations.

In December of 2015, during the 21st edition of the *Conference of Parties* (COP[7]) in Paris, France, on rare but hopeful sign of global unity and alignment to address the climate crisis, an agreement aimed at preventing the Earth's temperature from rising by more than 2℃ relative to pre-industrial levels was negotiated and consensually adopted by more than 190 nations (most of which formally signed the agreement in April of 2016) [12]. Despite being a non-binding and unenforceable accord, the *Paris Agreement* marked a new chapter in the international stage as a clear acknowledgement of the problem by world leaders, even though its translation into national policies and legislation is seen as much less clear and still questionable.

Almost four years later, in October of 2019, the *Intergovernmental Panel on Climate Change* (IPCC) issued a report emphasizing the importance of accelerating global efforts to mitigate climate change. In the report, the agency, which is composed of scientists and researchers studying and monitoring climate patterns, highlights the importance of keeping temperatures from rising more than 1.5℃ – a level deemed "ideal" by the Paris Agreement. It further states that the seemingly small difference between a 1.5℃ and 2℃ scenario could be crucial to avoid catastrophic consequences worldwide, many of which are not fully understood. If the promises made from the French capital during *COP-21* are to be kept, business as usual must not be an option going forward.

[7] COP is an annual meeting of the United Nations Framework Convention on Climate Change (UNFCCC) Parties to review their emission inventories and measures as a way to assess progress in dealing with climate change [11].

1.2.2. Decarbonisation

Transitioning the world's ninety-trillion dollar economy [13][14] from consuming one hundred million barrels of crude oil daily [15] to a low-carbon and sustainable energy system is an extremely daunting challenge in and of itself; and might be considered simply unattainable when combined in a time horizon of a few decades. Hard as it may seem, this would not be the first energy transition humans go through. The composition of our energy supply has been evolving for millenia, from systems based on traditional biofuels (i.e. wood) prevalent for thousands of years, to a fossil fuel one since the Industrial Revolution in the 18th century coal (in addition to a few other alternatives that have appeared more recently, such as nuclear energy) – Figure 4.

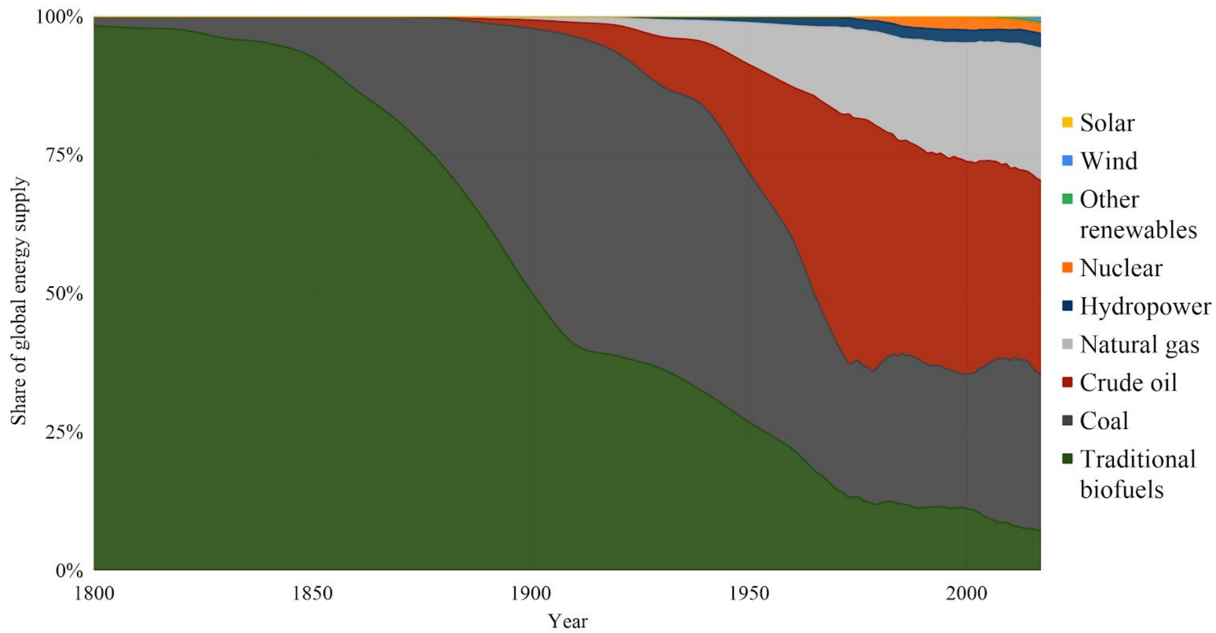

Figure 4 - World's primary energy consumption by energy source[8] [16][17]
(Elaboration: author)

A crucial consideration when discussing a paradigm shift of the global energy supply is its scale and, consequently, the inertia of the current apparatus. Over the last two centuries, the world has witnessed a slow transition away from traditional biofuels towards fossil fuels (i.e. coal, oil and natural gas), in combination with an exponential growth in energy consumption per capita – which has more than tripled since 1800, from about 20 gigajoules per person per year back then, to more than 65 gigajoules in 2010 [16][18]. This has led to an increased dependence on fossil

[8] *Traditional biofuels* include wood fuels, agricultural byproducts and dung burned mainly for cooking and heating purposes. *Other renewables* include renewable sources apart from solar, wind, hydropower and traditional biomass. The most notable examples are: geothermal, wave, tidal, and modern synthetic biofuels (e.g. ethanol).

fuels, making a transition to a low-carbon mix an incredibly onerous and slow undertaking at a global scale (Figure 5).

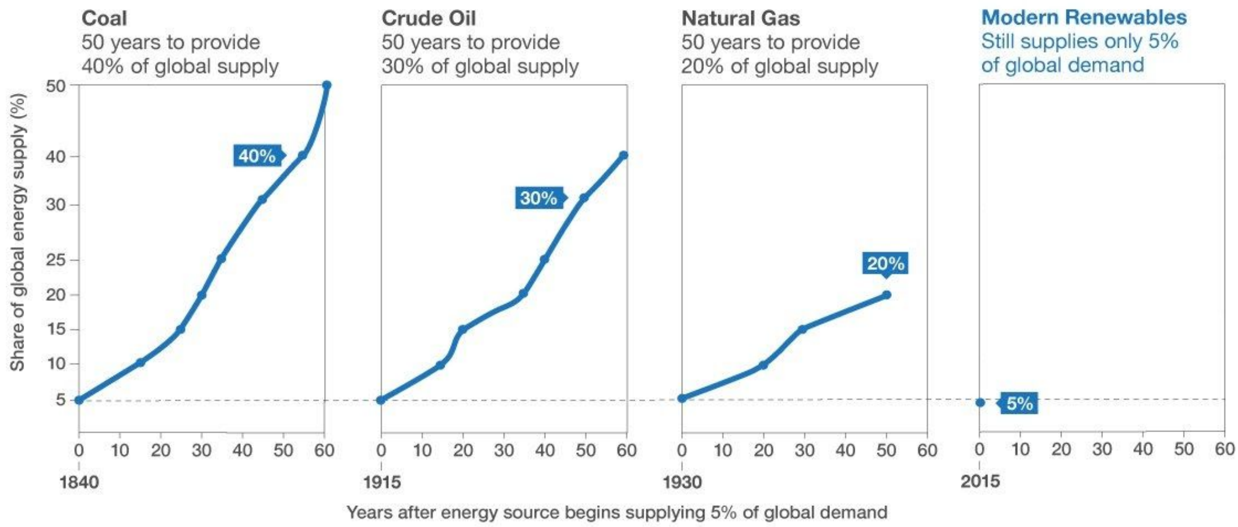

Figure 5 - Energy transition time by energy source[9] [16]
(Elaboration: Gates Notes [19])

The *Kaya Identity* (Equation 1) is a simple and yet insightful equality that uncovers the fundamental drivers of global emissions and the ways one can go about eliminating them:

$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \qquad \text{(Equation 1)}$$

where F is carbon emissions, P is population, G is gross domestic product (GDP) and E is energy input (consumed). Based on *Kaya's Identity*, for carbon emissions (F) to be zero (or close to it), at least one of the terms of the multiplication must be zero (or close to it). Let's look at each one and analyse the feasibility of bringing them to zero (or close to it).

The first term is the population (P). It is safe to assume that most people would find it undesirable (and unpleasant) to try to bring the world's population close to zero. The next term is GDP per capita (G/P). Given the correlation between living standards and economic output, ideally this term should continue to increase as developing nations "catch-up" with the developed world and more people climb out of poverty. Next up is the energy intensity of the global economy (E/G). Energy input per unit of GDP can definitely be reduced to a certain extent, with technological innovation that makes processes more efficient; but at the limit, it cannot possibly be zero (or even close to it), as efficiencies are capped below 100% by the laws

[9] *Modern renewables* include wind, solar photovoltaic and modern synthetic biofuels.

of thermodynamics and energy will always be needed to maintain a functioning society. Finally the last term is the carbon intensity of the energy consumed (*C/E*). Carbon emissions per unit of energy input can, in theory, be brought to (near) zero by using clean energy sources. For a significant share of our energy consumption (e.g. electricity), proven carbon-free technologies already exist: solar, wind, hydro and nuclear energy, to name just a few. Granted, there is still a need to develop new ones to decarbonise *hard-to-abate*[10] sectors and overcome some key limitations of existing ones; nevertheless, there is no fundamental reason or law of physics why the carbon intensity of our energy use could not be zero (or at least close, very close to it).

1.2.3. The power sector

Let's have a look at electricity, one of the most versatile and widely used energy vectors. Electricity has played an important role as an energy carrier since the proliferation of power networks in the 20th century. It is so ubiquitous to modern life that its unique properties are seldom appreciated. Electricity is a high-grade[11] energy vector that is 100% clean at point of use while remaining extremely fungible. It can be generated from several different energy sources and its transportation (i.e. transmission) over long distances – hundreds and even thousands of kilometers – incurs relatively low losses, in the order of 5% for modern electrical grids.

In an ever more electrified economy, where industrial machines, home appliances, electronic devices and vehicles are powered by moving electrons, electricity can serve as a powerful instrument to help the world to transition to a sustainable energy future. By coupling the electrification of processes with the deployment of clean and renewable power generation, electricity can be a carbon-free energy carrier not only at point of consumption, but across its entire value chain.

In order to better understand how electricity can help with the decarbonisation of the energy sector, it is important to assess its *state-of-the-art* and the ways in which it can be leveraged going forward. In 2017, electricity generation represented approximately 21% of all the energy

[10] Sectors of the economy that are hard to decarbonise with current commercial technologies: cement, chemicals such as plastics and fertilizers, steel, aviation and shipping (i.e. transcontinental cargo ships).
[11] Pure exergy (energy that can be converted to useful work).

consumed globally [20]. Power generation was responsible for about a third[12] of global energy-related carbon emissions [21], with two thirds coming from fossil fuels (Figure 6).

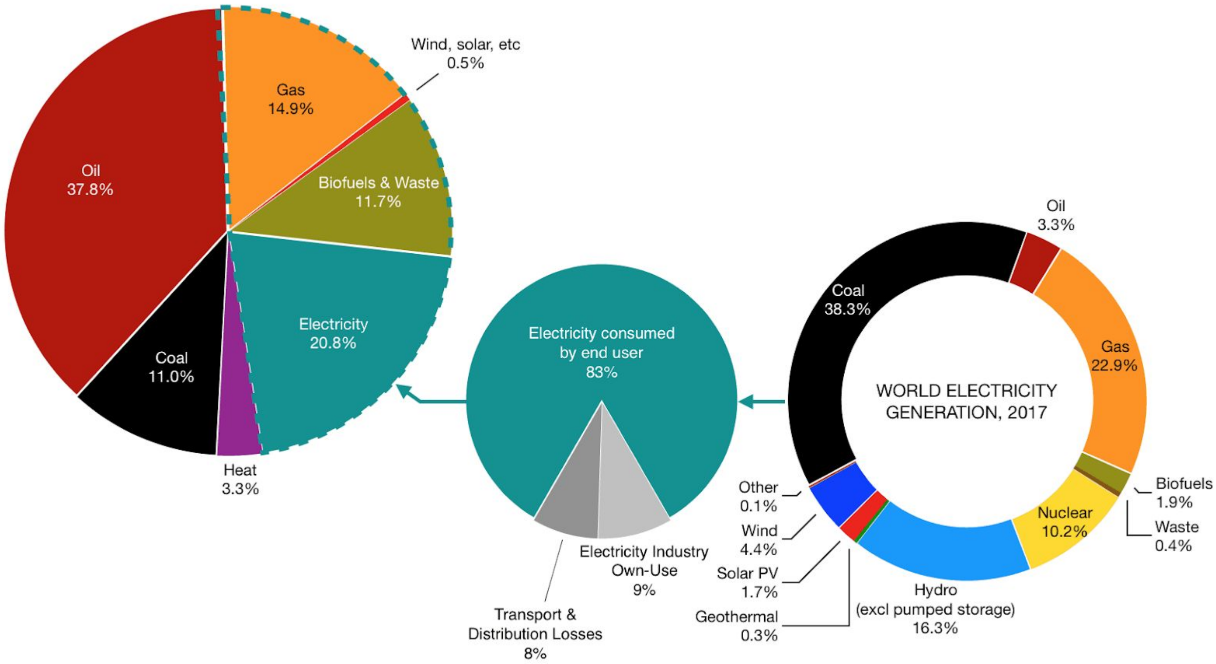

Figure 6 - 2017 global final energy consumption by source [22] (Elaboration: Worldenergydata.org [23])

Despite our high reliance on fossil fuels (Figure 6), there already exists a mix of clean and renewable power technologies that can be combined to decarbonise the electricity sector. Hydroelectricity, solar[13] and wind energy, batteries and (green[14]) hydrogen are a few examples of technologies that can already be commercially deployed.

Electrification – from industry to transport, manufacturing to heating – if coupled with clean and reliable power generation, represents a clear first step for the decarbonisation of the energy sector. There are several challenges to be overcome, as we do not yet have the answers to the entire problem set; but that should not hinder the implementation of the solutions we do have. Collaboration between the public and private sectors, politicians and business leaders, researchers and scientists, engineers and citizens ought to lead to new discoveries that will bring the rest of the answers needed, and in time.

[12] Estimates from the IEA, IPCC and the World Resources Institute range from 25% to 40%.
[13] The two main solar energy technologies are solar photovoltaic (PV) and concentrated solar power (CSP).
[14] Hydrogen gas (H_2) produced via electrolysis (power-to-gas) using clean and renewable electricity.

2. Introduction

The decarbonisation of what has become an extremely energy intensive economy is an immense undertaking that challenges us to rethink complex established systems at a global scale. In practice, however, measures can only be feasibly implemented at local and more individual subsystems for which a viable solution can be identified and deployed[15].

Greenhouse gas (GHG) emissions from human activity are often categorized by sector: agriculture and forestry; industry; commercial and residential; transportation; electricity and heat. One of the domains for which the decarbonisation process is steadily underway is electricity. The rapid advances experienced by clean and renewable technologies such as solar photovoltaic (PV) and wind energy, in combination with progressive climate agendas being pushed by governments across the world – most notably in Europe[16] – have drastically reduced the cost of such technologies, driving a significant increase in their demand during the last decade and setting an upward trend that is expected to continue in the coming years (Figure 7).

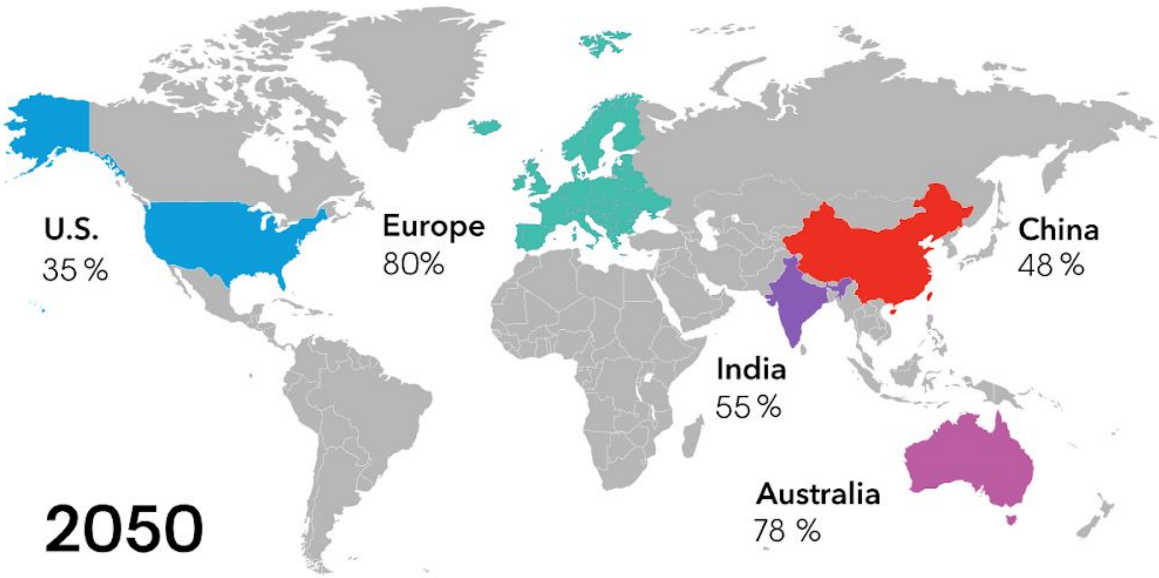

Figure 7 - Solar and wind penetration in the energy mix in 2050 [24] (Elaboration: BNEF)

The growing economic competitiveness of renewable energy technologies relative to fossil fuels has attracted more than 2.5 trillion dollars in investments from 2010 to 2019. This capital flow has funded projects worldwide, quadrupling global renewable capacity from 414 GW in 2010 to

[15] Think of the answer to the question "how do you eat an elephant?".
[16] Through a series of incentives and market schemes employed by Member States, the European Union is at the forefront of global decarbonisation with some of the most progressive and comprehensive climate policies.

about 1,650 GW[17] in 2019 [25]. The increased penetration of renewables in power systems present some notable integration challenges, especially in view of the intermittency of solar PV and wind energy and their effect on the stability and reliability of electrical networks.

2.1. Objectives

In order to examine the prospects for decarbonization of a power system, taking into consideration costs (financial and environmental), technical constraints and system reliability, it is important to define clear boundaries, ideally isolating the area subject to the analysis from its surroundings. Since we don't live in an idealized world, but in one of intricate interdependencies and ripple effects, such ideal "laboratory conditions" are approximated by establishing a well-defined setting to be studied based on its resources and needs.

Luckily, our non-idealized world contains a group of subsystems that fit this criteria well enough for such an examination to be carried out: *islands*. Nowadays they are almost never completely isolated from the rest of the planet, but islands still present a specific set of characteristics that, in many ways, require a certain level of balance between local natural resources and human demand[18].

Against this backdrop, the objective of this study is to model an optimized power system for the decarbonisation of an island. More specifically, it consists of a techno-economic analysis of the power system of the Spanish island of Menorca (Figure 8). Computational models assessing a series of power technologies with their respective costs and technical specifications are analysed through a series of simulations. The final goal is to identify the lowest-cost system that can reliably meet the electricity demand of Menorca while reducing local carbon emissions. The study is conducted for a time horizon of ten years, from 2021 to 2030 (inclusive).

2.2. Scope

Menorca was declared a biosphere reserve by UNESCO in 1993, "in recognition of the high level of compatibility between the development of economic activities, the consumption of resources, and the conservation of heritage and landscapes" [26]. As such, authorities and

[17] Excluding hydro power plants larger than 50 MW.
[18] By extrapolation, Earth can be interpreted in the same way: an island of the cosmos.

citizens of Menorca have a keen interest in the implementation of sustainable solutions that promote a balance between socio-economic development and environmental preservation.

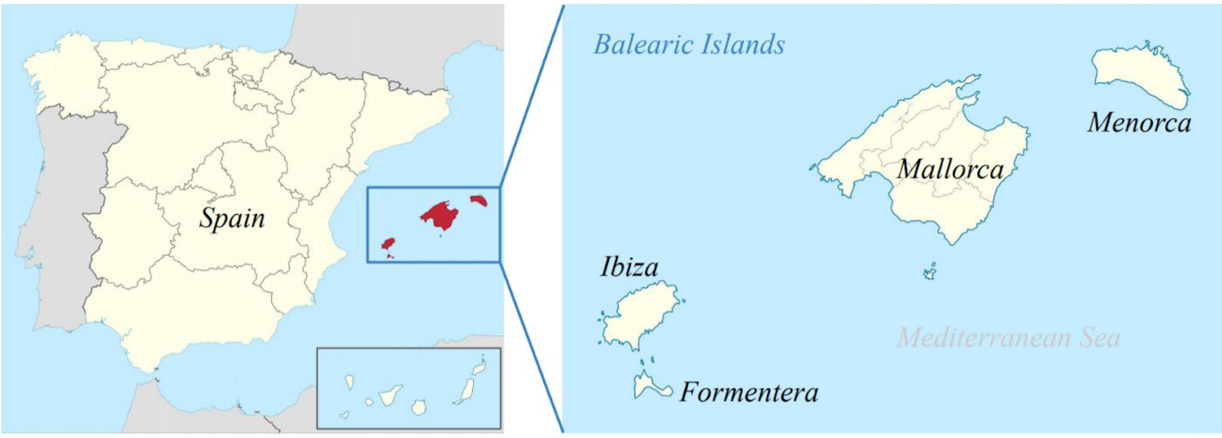

Figure 8 - Map of Spain highlighting the Balearic Islands [27] (Elaboration: author)

Menorca is an especially interesting case study due to its current high dependence on liquid fossil fuels (mainly fuel-oil[19] and diesel) for power generation, the high seasonal variability of demand caused by its prominent tourism industry and the local government's aggressive climate agenda, such as the proposed target of 85% renewable power generation by 2030.

Studies carried out by *IME – Institut Menorquí d'Estudis* (Menorcan Institute of Studies) in collaboration with *CIME – Consell Insular de Menorca* (local council), *GOB – Govern Illes Balears* (Government of the Balearic Islands) and local agencies such as *Menorca Reserva de Biosfera* (Menorca's Biosphere Reserve) to assess the island's energy system and carbon footprint have resulted in the formulation of a decarbonisation strategy to be implemented in the coming years as a part of the *Estratègia Menorca 2030* (Menorca Roadmap 2030) initiative.

Thus far, two reports[20] have been released, for the years of 2018 and 2019, by *IME* under the *Directrices Estratégicas de Menorca* (Strategic Guidelines for Menorca), detailing the current situation of the island's energy sector and laying out a target-based plan to reduce the island's dependence on fossil fuels and lower its carbon emissions. The plan is built on five core principles (Figure 9).

[19] Fuel-oil in this report shall refer to the liquid petroleum derivative fuel that is also commonly referred to as heavy oil, bunker oil or residual oil [28].
[20] The reports, entitled *Menorca's First Energy Transition* and *Menorca's Second Energy Transition*, are available to the public on *IME's website* in Catalan, Spanish and English.

Figure 9 - Principles and criteria of Menorca's Energy Transition [29] (Elaboration: author)

The information and data from the reports shall serve as reference for some of the parameters used to model Menorca's power system. However, it must be noted that IME's analysis covers the entire energy use of the island, whereas the study herein presented, together with all the calculations and computational simulations performed, is only concerned with modelling the power system, represented by the island's use of electricity.

Moreover, the model ought to be implemented as an optimization algorithm to determine the lowest cost power system capable of reliably meeting Menorca's electricity demand while progressively lowering its carbon footprint. The possibility to constraint the optimization based on predefined parameters, for example a renewable portfolio standard (RPS) or a carbon price, are also evaluated by the examination of different scenarios. Their respective results shall allow for comparisons and conclusions to be drawn, helping identify the most effective approach for the decarbonisation of Menorca's power sector.

Although guided by the general principles presented in the *Estratègia Menorca 2030* roadmap, this study aims to independently assess how the decarbonisation of Menorca's power system can be done in a pragmatic fashion. Hence, different power generating technologies – including fossil-based ones (e.g. natural gas) – are considered based on their specific merits. This way, the cost-optimum system identified by the model can be analysed and compared to alternate solutions independent of uncertain externalities such as subsidy schemes and carbon taxation[21].

2.3. Case study: the island of Menorca

Menorca, the northernmost Balearic Island (Figure 8), has a population of about 94,000 inhabitants [30]. Despite having the second largest territory (behind Mallorca), with a surface

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[21] Any scenario considering asymmetric market interventions or incentives is clearly described and justified as such.

area of 701 square kilometers, it is the third most populous of the four Balearics[22]. The island has a total of 8 municipalities (Figure 10). The two biggest ones, *Mahón* (the capital) located on the east side, and *Ciudadela de Menorca* located on the west side, account for more than half of the total population. Despite temperatures averaging 18-20℃ throughout the year, they often go above 30℃ in the hottest summer days, while in the winter they can dip close to 0℃.

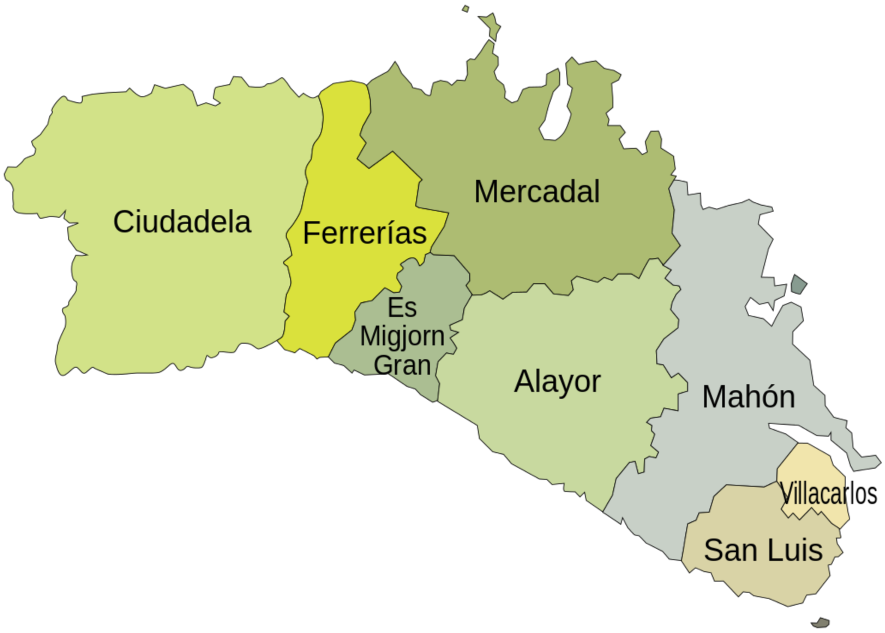

Figure 10 - Map of Menorca and its municipalities [31]

With an economy largely based on tourism, travelling to and from Menorca is easy given the well-connected airport on the east side of the island and several ports along its coast. As a result, the number of people on the island can surpass 200,000 during the summer due to the high influx of tourists [32]. Menorca received more than 1.5 million visitors (more than 10 times its official population) between the months of April and October of 2018 [33]. Aside from tourism, the main economic activities in the island are general agricultural practices, shoe manufacturing and a prominent cheese industry with its well-known and sought-after *Queso de Mahón*.

Menorca's status as a biosphere reserve, designated by UNESCO in 1993, is testament to the island's success harmonizing socio-economic development and environmental sustainability. Nevertheless, the seasonal pressure of such vigorous tourism and hospitality industries on local resources is endangering regional ecosystems and provoking unintended consequences on the welfare of the island's residents.

[22] The four Balearic Islands (by descending order of population) are: Mallorca, Ibiza, Menorca and Formentera.

2.3.1. Power system

The challenge of balancing economic prosperity and ecological conservation is notable in Menorca's electricity system, which must cope with a high degree of seasonal variability with a limited amount of local resources at its disposal. Menorca consumed approximately 500 gigawatt-hours (GWh) of electricity in 2019, with instantaneous power demand peaking close to 120 megawatts (MW) during the hottest summer days (high season). This peak is virtually halved during the low season to about 60 MW, when demand for cooling is much lower and a lot less tourists are roaming the island's streets (Figure 11).

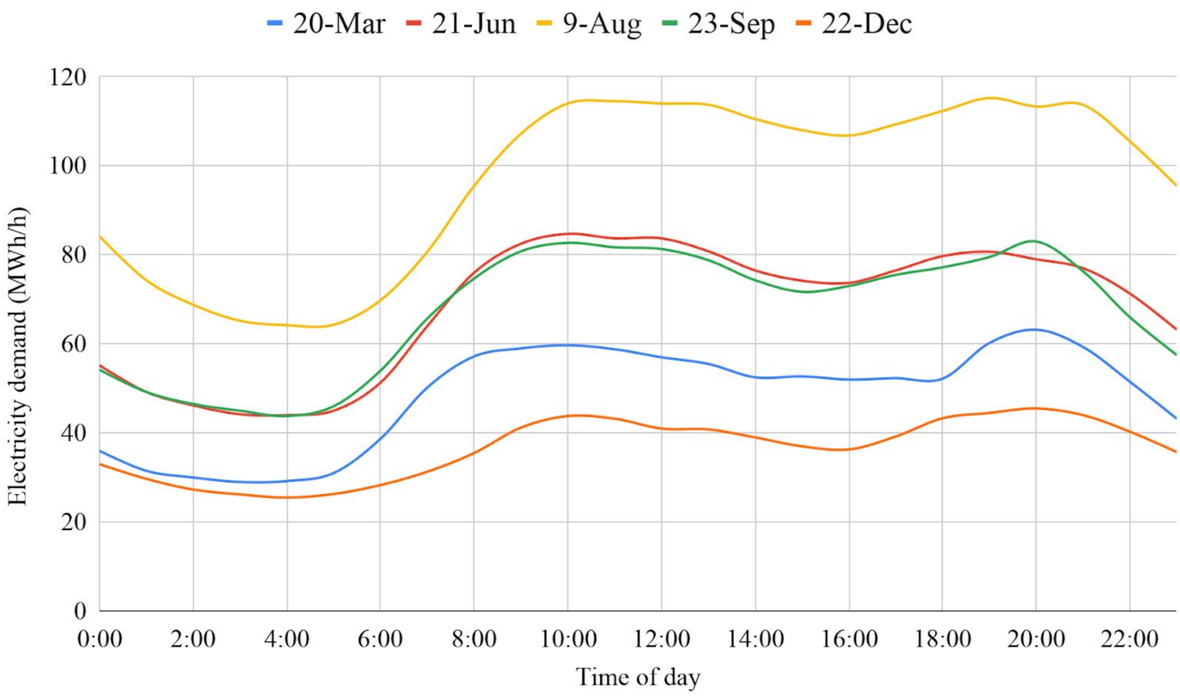

Figure 11 - Menorca's hourly electricity demand for select days[23] in 2019 [34] (Elaboration: author)

From the early 1980s to the autumn of 2017, Menorca was electrically connected to Mallorca (the biggest of the four Balearic Islands) through a high-voltage alternating-current (HVAC) sea-cable with a transmission capacity of 35 MW, operating at 132 kV [35]. The submarine interconnection, one of the first of its kind to be deployed in Spain, was built in the 1970's [36] and remained operational until a boat anchor accidentally fell on it in October of 2017, causing irreversible damage[24]. From that point on, Menorca was electrically isolated from any other power system, fully relying on local power plants to meet local electricity demand.

[23] Solstice and equinox days, and August 9th, which was the day with the highest hourly demand (peak) of 2019.
[24] After more than 35 years, the cable was operating beyond its expected life and was due for a replacement.

Local generating capacity is heavily concentrated on a single thermal power plant: GESA. Located in Mahón, it is owned and operated by the utility company Endesa (Figure 12). With a total capacity of 271 MW, the plant's generators run on diesel (224 MW) and fuel-oil (47 MW).

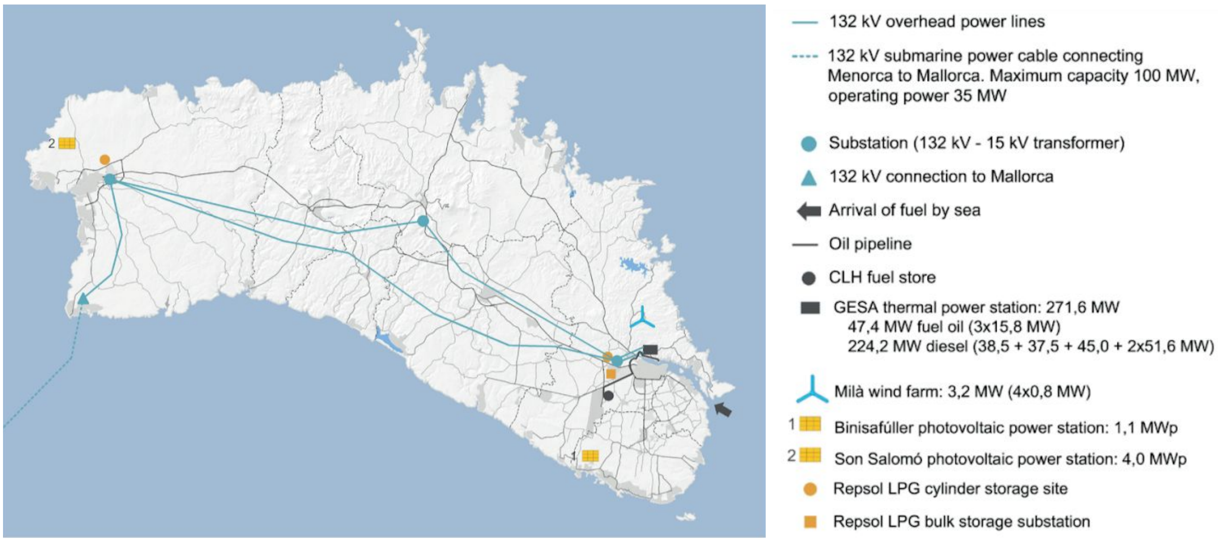

Figure 12 - Map of Menorca's power system [37]

Renewables play a very marginal role in Menorca's power generation mix, consisting of one wind power plant with 3.2 MW of capacity (4 turbines of 0.8 MW each) and two solar PV plants totalling 5.1 MW_p (Figure 12). Together, solar PV and wind account for about 3% of the island's annual electricity supply, leaving 97% to be supplied by GESA's fossil-based generators.

In order to improve the resilience of the island's electrical system, the Spanish transmission system operator (TSO), *Red Eléctrica de España* (REE) – who is responsible for the construction, operation and maintenance of transmission power lines across the country – finished installation of a new submarine cable connecting Menorca to Mallorca in November of 2019. The HVAC interconnection extends for 41 km underwater, 12.4 km on land to a substation in Ciudadela, Menorca; and another 800 meters from its other end to a substation in Cala Mesquida, Mallorca. Weighing 2,300 tonnes, the cable has a total capacity of 100 MW at the same 132 kV as its predecessor. Operation, which began in June of 2020[25], after necessary tests and inspections were conducted, is capped around 35 MW due to technical requirements.

The 84 million euro investment made by REE in the new interconnection aims to make Menorca's power system more reliable and increase energy security. Given the existing

[25] Interestingly, the new cable came online on June 17^{th}, 2020, the same week this section of the report was written.

submarine HVDC transmission line between Mallorca and Valencia[26], the new cable allows Menorca to significantly reduce its electricity-related emissions by importing cleaner power (through Mallorca) from the Spanish Peninsula (Figure 13).

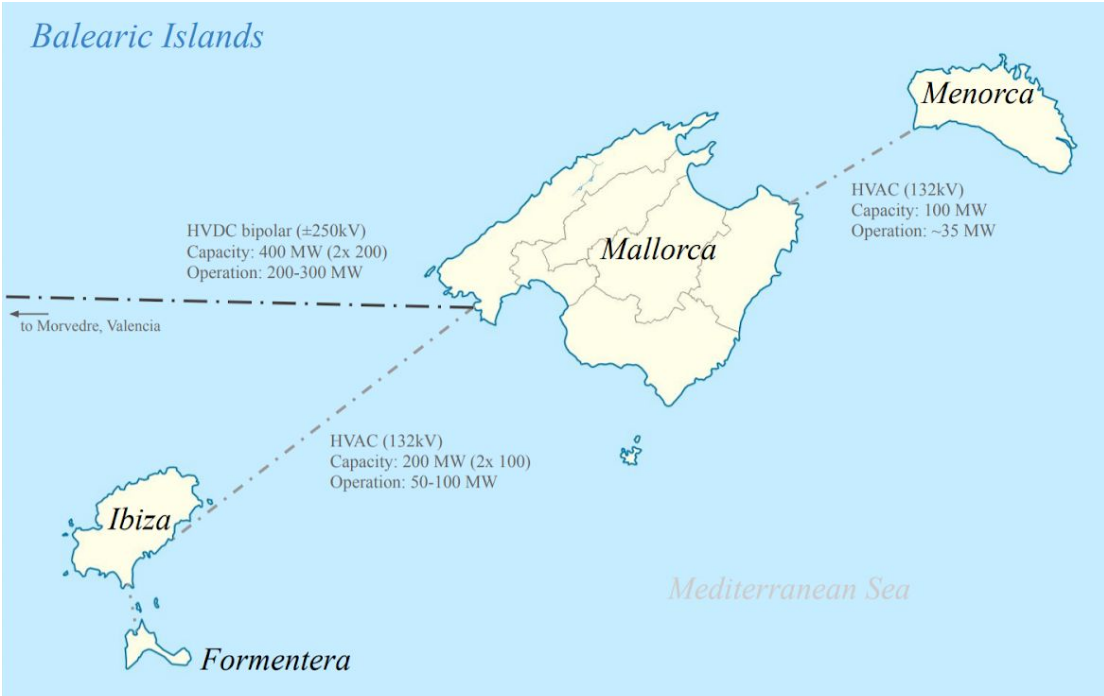

Figure 13 - Electrical submarine interconnections of the Balearic Islands [39] (Elaboration: author)

2.3.2. Emissions

Islands face several additional complexities for the development of a robust and reliable electrical network. In the case of Menorca, land availability, the cost of importing goods (e.g. fuels) and the seasonal effect of tourism on local markets directly impact the efficiency and competitiveness of its energy system. After being electrically disconnected from Mallorca in 2017, Menorcans relied on the GESA thermal power plant for generation of more than 95% of the island's electricity supply. The plant's outdated generators – running on fuel-oil and diesel with efficiencies of around 33%[27] – are responsible for more than half of Menorca's carbon emissions, despite only accounting for a third of the (final) energy consumed in the island [40].

Aside from GHGs, the combustion of liquid petroleum-derived fuels (i.e. fuel-oil and diesel) significantly contributes to air pollution through the emission of nitrogen oxides (NOx), sulphur oxides (SOx), carbon monoxide (CO) and particulate matter (PM). These substances are

[26] An HVDC bipolar submarine cable (i.e. project *Rómulo*) with 400 MW of capacity operating at ±250 kV [38].
[27] Two thirds of the energy present in the fuel consumed by the generators is dissipated as thermal waste.

dangerous not because of their global warming potential (GWP), but mainly due to their toxicity and harmful impact on human health and the environment[28]. Long term exposure to NOx and SOx contributes to respiratory illnesses (e.g. asthma, chronic bronchitis), decreased lung and liver function, inflammations, and increased risk of allergy and cardiovascular conditions [42].

Menorca's high reliance on fossil fuels for power generation (at the GESA thermal plant) makes its electricity-related carbon footprint four times higher than that of Spain (Figure 14–left). In addition, the use of diesel and fuel-oil by the power plant's generators is a major contributor to air pollution, being responsible for more than two thirds of the island's NOx and SOx emissions [37], which are also significantly higher than Spain's national levels (Figure 14–right).

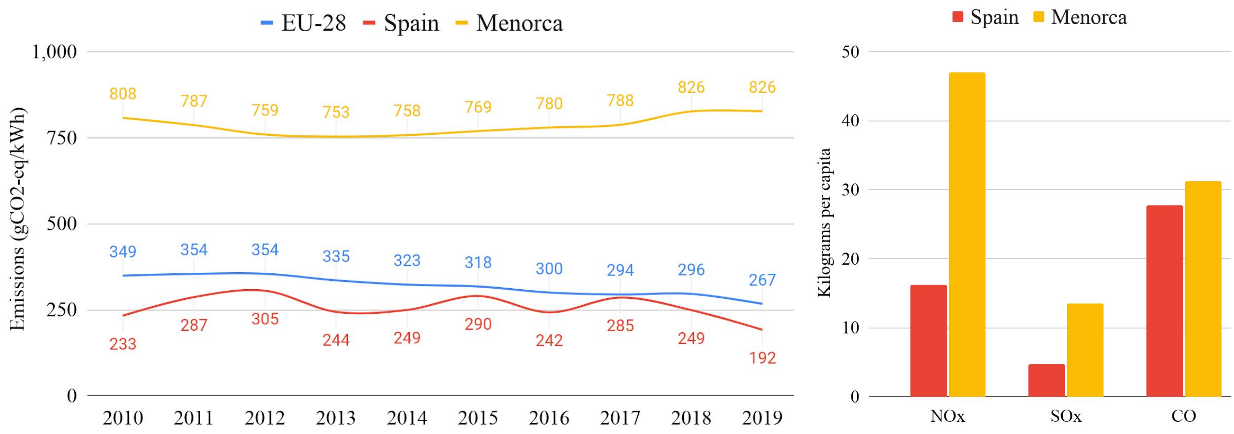

Figure 14 - Electricity-related CO_2 emissions (left). NOx, SOx and CO emissions, 2013 (right) [37][43][44][45][46][47][48] (Elaboration: author)

The impact of the GESA thermal plant on the well-being of local residents, especially in the Mahón region, is a growing concern among citizens. Activists from the group *NoTòxicMenorca* advocate for the power plant to be closed and replaced by clean and renewable alternatives.

Despite the aforementioned challenges of developing sustainable and competitive solutions for island territories, the steep cost reductions experienced by clean and renewable technologies in the last decade represent a clear opportunity for Menorca to redesign its power system. A complete overhaul of the local generation capacity, in a well coordinated and integrated fashion, constitutes a clear path for the island's decarbonisation, helping preserve its biosphere and high ranking as a tourist destination, in full alignment with the *Estratègia Menorca 2030* roadmap.

[28] In the atmosphere, emissions of sulphur and nitrogen compounds are transformed into acidifying substances such as sulphuric and nitric acid. In the ground, they cause the acidification of the soil and water, contributing to forest damage, eutrophication and severely impairing the local flora and fauna [41].

3. Methodology

The implementation of a comprehensive and pragmatic decarbonisation plan for an island the size of Menorca ought to take into consideration a wide range of parameters, from operating technical constraints that ensure a reliable and stable electrical network, to the socio-economic implications of the transition to the proposed system, including the investments needed to finance the transformation, eventual impacts on prices and the welfare of the local community.

The decarbonisation of power systems is often planned and designed based on distorted and manipulated assumptions to ensure the results fit a pre-established narrative, usually driven by either political discourse and/or corporate interests. A clear and common example of such idealistic approach is the inclusion of technology specific incentives[29] (e.g. subsidies) that distort market dynamics, jeopardizing areas of the economy that can derive efficiency gains and lower prices from competition.

One prime example of such a phenomenon is Menorca's power system. Due to the high costs of generating power locally (at the GESA power plant) and the current lack of alternatives – effectively no competition – the electricity sector is regulated[30] and highly subsidized to ensure the local population pays prices consistent with Spain's peninsular power market. It is estimated that together, fossil-based power plants in the Balearic islands receive between 250-300 million euros in annual subsidies to keep electricity prices similar to those observed in the deregulated Iberian power market (*Mercado Ibérico de Electricidade* or MIBEL), which covers the electrical systems of Spain and Portugal [49].

In order to avoid such asymmetries and distortions, the computational modelling and analysis of Menorca's power system shall be implemented in a technology-agnostic approach that is devoid of any agenda (political or otherwise) and is aimed at identifying a cost-optimum solution. Moreover, technological limitations, technical constraints and operational requirements are integrated into the model to ensure the results of the techno-economic analysis are objective and practical.

[29] Incentives are not intrinsically harmful, and have played an important role in the development of clean and renewable technologies such as solar PV and wind energy. However, their inclusion in the long-term planning of complex systems (i.e. power systems) can be misleading due to the distortion of market signals.
[30] Different from the liberalized model adopted by Spain and most European nations.

It is worth noting that the decision to model Menorca's power system and the optimization algorithm around the most cost-efficient mix of technologies that can meet the island's needs in the next 10 years (2021-2030) is a deliberate one. Therefore the goal is not to find the solution with the lowest carbon footprint, but the most cost-efficient one (Figure 15).

Nevertheless, the resulting carbon emissions – a key aspect of any decarbonisation plan – ought to be incorporated in the analysis as an externality, for example, through a carbon pricing scheme similar to the European Union's Emissions Trading System (ETS). This way, the environmental benefits of clean technologies are taken into consideration as avoided carbon costs that are otherwise incurred if carbon-emitting energy sources are used.

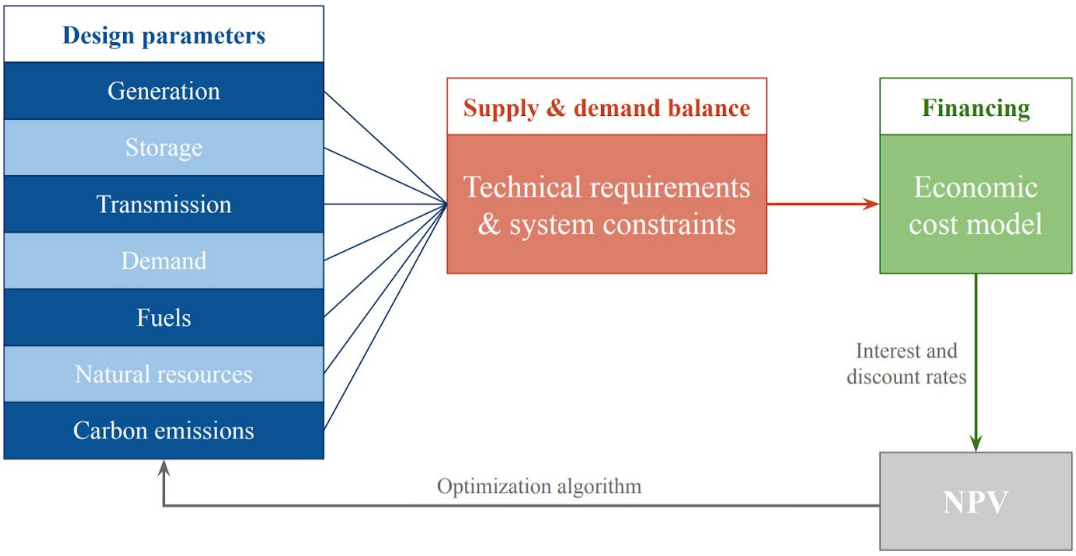

Figure 15 - Power system model and optimization structure (Elaboration: author)

By keeping the model strictly guided by technical requirements, system constraints and cost parameters, the results can effectively point to a viable decarbonisation strategy to be developed by public and/or private entities in a market-driven approach where capital is allocated efficiently. Moreover, the described techno-economic optimization shields the analysis from any political or subjective bias, generating results purely based on the merits of each technology considered and the value they add to the modelled system as a whole.

Finally, in order to better understand the model's sensitivity to variable parameters (e.g. future fuel costs, carbon prices and renewable portfolio standards), different scenarios are implemented and compared (Section 3.2.2.).

3.1. Computational model and optimization

In order to perform a techno-economic analysis of Menorca's power system and identify the most cost-efficient set of technologies that can meet the island's electricity needs, a computational model that incorporates all of the relevant characteristics and parameters must be created. Once the model is built, an optimization algorithm can be run based on a predefined set of constraints, requirements and an objective function[31].

Due to the computational intensity of modelling and optimizing a system composed of hundreds of variables that can be combined in millions of different permutations, the use of specialized software designed to perform such analysis is required. Table 1 compares a few alternatives.

Model	*Multiple investment periods*	*Inter-hour relationships*	*Generator unit commitment*	*User-defined extensions*	*Low-cost or open-source*
TIMES/MARKAL	✓		!	✓	!
NEMS	✓		!		!
LEAP + OseMOSYS	✓		!	!	✓
Balmorel	✓		!	!	!
E4 Simulation Tool	✓			!	!
Oemof		✓		✓	✓
URBS		✓		!	✓
PyPSA		✓	✓	✓	✓
PLEXOS LT Plan	✓	!	!	!	
RESOLVE	✓	✓	!	!	✓
RPM	✓	✓	✓	n/a	
Switch 2.0	**✓**	**✓**	**✓**	**✓**	**✓**
(✓) Fully supported (!) Partially supported (n/a) Model not available to external researchers					

Table 1 - Feature comparison of some power system capacity planning software packages [50]

Switch (version 2.0) is the computer program of choice to model Menorca's power system and perform the techno-economic analysis proposed. It is written in the programming language Python as an open-source[32] package and is freely available for use (and customization) by the general public, making it uniquely versatile and flexible for this study.

[31] The objective function represents the variable the algorithm optimizes for, usually by identifying the set of inputs that result in a global maximum or minimum, while simultaneously meeting the predefined requirements and respecting the established constraints.

[32] Open-source software is a type of computer program that has the source code released under a license in which the copyright holder grants users the rights to use, study, change, and distribute the software to anyone and for any purpose [51]. This is especially relevant as it allows for the study and results herein presented to be replicated.

3.1.1. Power system modelling tool: *Switch 2.0*

Switch 2.0 is composed of several modules that together define the power system model, while the optimization itself is implemented through *Pyomo*, a separate (also open-source) general purpose modelling framework. *Pyomo* converts the Switch model into a standardized, computer-readable form and sends it to an external solver[33] (e.g. GLPK, CBC, Cplex or Gurobi), which, in turn, does the intense computation required to find the optimum solution [52].

Because *Switch 2.0* uses a modular, bottom-up approach to define power system models, it allows for individual elements to be modified and adjusted according to the user's specific needs. With a structure composed of modules and subpackages, elements can be modelled independently, while their combined interaction at the system level contributes to the model's requirements, for example: power balance, operating reserves, unit commitment, etc (Figure 16).

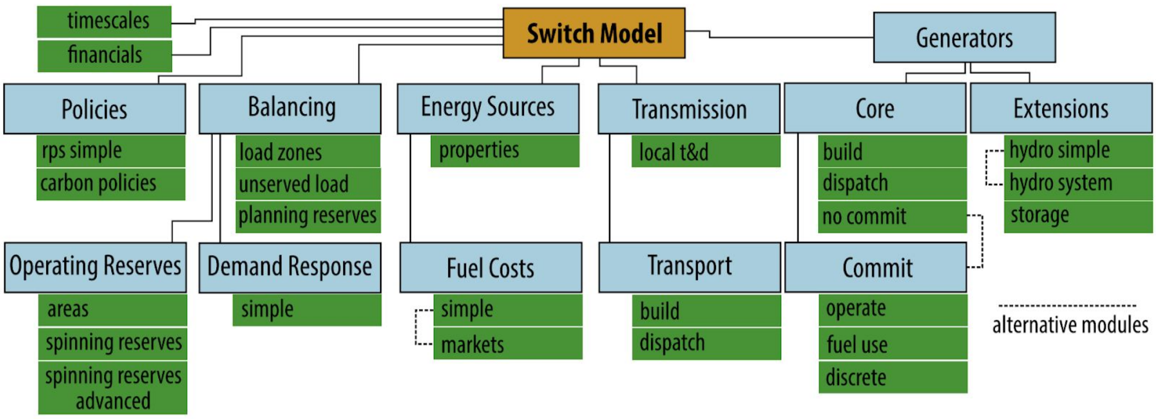

Figure 16 - *Switch 2.0* structural framework (blue: subpackages; green: modules) [50]

Despite a seemingly complex structure, *Switch* can operate based on a relatively simple set of inputs, so long as they are enough to define the power system and constraint its operation to a finite number of solutions. The more variables (i.e. modules and consequently inputs) included in the model, the higher the optimization's order of complexity (more permutations possible).

In summary, *Switch* works by populating the model with user generated inputs (*.dat* or *.tab* format text files) and generating an optimization problem in matrix form. The problem is passed to the solver for the computational process, which is guided by user-defined parameters: system constraints, optimality gap and other solver options (Figure 17) [53].

[33] *Switch* works with different linear and mixed integer programming solvers: GLPK, CBC, CPLEX and Gurobi. CPLEX, an IBM proprietary solver, is used for this study.

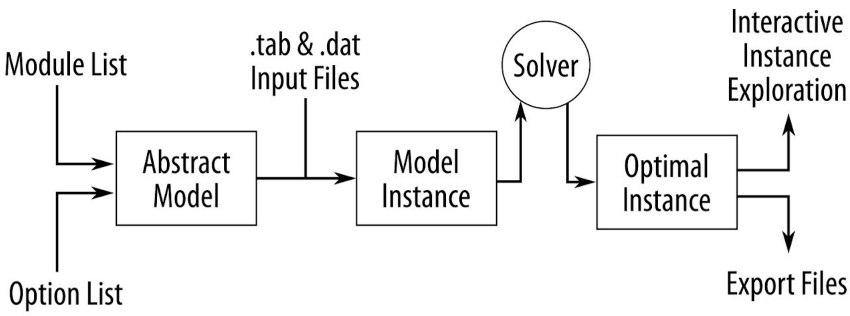

Figure 17 - *Switch's* process of formulation and solving of single scenarios [53]

3.1.2. *Switch*'s modelling architecture

Despite the possibility for the user to create and integrate custom modules to *Switch*'s architecture, the software includes several core and optional ones, which have been implemented as part of the updated open-source package by its original creator, *Matthias Fripp*[34], Ph.D. A quick overview[35] of the main default subpackages and modules (Figure 16) is pertinent to a proper understanding of the software's functionalities, properties and capabilities.

- *Timescales:* defined as a three-level hierarchy for temporal dimension variables:
  - *periods*: set of multi-year timescales that determine when the investment decisions are made;
  - *timeseries*: set that denotes blocks of consecutive *timepoints* within a *period*. An individual *timeseries* could represent a single day, a week, a month or even an entire year;
  - *timepoints*: set that describes unique time steps within a time series. The duration of a *timepoint* is typically on the order of one or more hours, so costs associated with *timepoints* are specified in hourly units;
- *Financials*: defines the financial parameters used to discount future expenditures (CAPEX and OPEX) to their net present value (NPV) and to calculate annualized cost of investments. The results define the optimization's objective function (Section 3.1.3.1.).
- *Balancing*: defines the electrical load zones and geographic regions with load *timeseries* in which supply and demand must be balanced at all *timepoints*.
- *Generators*: defines all possible generation projects based user-input data detailing specifications for different power generating units. *Switch* aggregates generators into generation projects, which are stacks of one or more similar generating units in the same transmission zone (thus subject to the same transmission constraints).

[34] Professor at the Department of Electrical Engineering, University of Hawaii at Manoa, Honolulu, HI, USA.
[35] A detailed explanation of *Switch*'s modules can be found in its original supplementary material [53].

- *Transmission*: *Switch* offers different approaches for representing transmission network capabilities. The most basic one being a single-zone (i.e. copperplate) formulation, which ignores restrictions on spatial transfer of power from one zone to another. Alternative implementations can be used to represent transmission capacities between zones.

- *Energy sources*: defines fuel (e.g. diesel, natural gas, etc.) and non-fuel (solar irradiation, wind, etc.) energy sources. Fuel costs can be implemented as a simple flat cost per period or through the *markets* module, according to regional supply curves and markets.

It is important to note that this list is not exhaustive[36] and is aimed at providing the reader with a brief overview of *Switch*'s modular architecture. Users are free to select the modules that are relevant to their study, keeping expendable complexities out of the model. Users can also create and integrate additional custom modules according to their specific needs.

3.1.3. *Switch*'s optimization formulation

Switch 2.0 modules contain – within each one – sets, variables, parameters and constraints. Because the modules interact with each other to define the power system being modelled, their components must be clearly defined. The following are the typographical conventions[37] that shall be used to explain part of *Switch*'s mathematical formulation[38]:

- Uppercase italic letters (e.g. P, T, G) define sets (collections of similar items);
- Lowercase italic letters (e.g. l, h, c) define parameters (input data) and indexes over sets;
- Lowercase italic letters with subscripts (e.g. c_p) reference arbitrary model components, generally selected from dynamic sets of model components;

3.1.3.1. Objective function

As previously mentioned, the objective function (i.e. the variable for which the model optimizes for) is the power system's total cost, which includes capital and operational expenditures (CAPEX and OPEX, respectively) of all assets deployed: generators, transmission lines, storage, fuels, etc. More specifically, the optimization algorithm searches for the solution that minimizes the net present value (NPV) of all investments made over the given lifetime of the model by

[36] A comprehensive list and explanation for *Switch*'s subpackages and modules can be found in its original supplementary material [53].
[37] These typographical conventions have been adapted from *Switch*'s original supplementary material [53].
[38] A detailed mathematical formulation can be found in *Switch*'s original supplementary material [53].

discounting all cash flows to a base year (an input), taking into consideration user-defined interest and discount rates (Function 1):

$$min \sum_{p \in P} d_p \left\{ \sum_{c^f \in C^{fixed}} c_p^f + \sum_{t \in T_p} w_t^{year} \sum_{c^v \in C^{var}} c_t^v \right\} \quad \text{(Function 1)}$$

where p is a time period component contained in the set of periods P. Each time period p represents a moment in which the decision to make a new investment – for example in a new power plant or transmission cable – is made by the algorithm; whereas the entire set of time periods P represents the lifetime of the model. C^{fixed} and C^{var} are the sets of fixed and variable costs, respectively. Each fixed cost component $c^f \in C^{fixed}$ is indexed by investment period p and specified in units of \$/year. Hence, the term c_p^f is the element with index p from component c^f (i.e. a fixed cost that occurs during period p). Each variable cost component c^v is indexed by timepoint t and specified in units of \$/hour [53].

Different modules may add different components to the fixed and variable cost sets to represent the additional costs that they introduce to the model. Thus, the cost function is dependent on the modules implemented and used. In general, fixed costs $c^f \in C^{fixed}$ include capital repayment for investments at a fixed interest rate over the lifetime of each asset, sunk costs from existing infrastructure, and fixed operation and maintenance (O&M) costs. Variable costs $c^v \in C^{var}$ typically include fuel costs and variable O&M. The weight factor w_t^{year} scales costs from a sampled *timepoint* to an annualized value proportional to the user-defined timeframe used for the set of *timepoints* (i.e. how many *timepoints* are contained in one year)[39]. The discount factor d_p (Equation 2) converts annualized costs from future periods to net present value [53].

$$d_p = \frac{1-(1+r)^{-y_p}}{r} \times (1+r)^{-(st_p - baseyear)} \quad \text{(Equation 2)}$$

where r is the annual real discount rate used to convert future cash flows to their present value; y_p is the length, in years, of period p; st_p is the year in which period p begins; and finally $baseyear$ is, as the name suggests, the base financial year to which future expenditures are discounted to (converted to their respective present values) based on r [53].

[39] Although the planning of power systems is commonly done using hourly time (or data) points, *Switch* does allow users to use custom intervals, which are scaled accordingly to the model's time periods.

3.1.3.2. Constraints

The main operational constraint of the model is the continuous balance between electricity supply and demand; in other words, the ability of power generating assets to meet the hourly electricity demand in Menorca. Given the variability of demand in time, this balance must be dynamically achieved by constantly adjusting power generation (ramping electricity production up or down), or consumption (e.g. demand response[40]). *Switch 2.0* has a specific module for the power balance (Figure 16) implemented according to Equation 3 [53]:

$$\sum_{p^i \in P^{inject}} p_t^i = \sum_{p^w \in P^{withdraw}} p_t^w \,, \quad \forall t \in T \qquad \text{(Equation 3)}$$

where power injections (generation) p^i, and power withdrawals (consumption) p^w, must be balanced during each *timepoint t*. The power balance (Equation 3) is expressed as an equality of two summations over dynamic sets of components that inject or withdraw power, P^{inject} and $P^{withdraw}$ respectively.

Other relevant constraints considered by *Switch*'s modelling formulation are the dispatch and commitment characteristics of generators, which include outages (planned and forced), minimum up and down times, transmission bottlenecks and variable capacity factors for intermittent non-dispatchable sources such as solar PV and wind energy.

In addition, deployment of generators can be bounded by capacity, for example, due to minimum generator unit size (lower bound) or limited availability of transmission capacity (upper bound). Other factors that affect the minimum and maximum capacities of each power technology may include the size of commercially available machines (e.g. gas turbines) or even land scarcity (especially relevant for islands). Optional modules may also be implemented to account for additional constraints such as contingency and spinning reserves, demand response, among others [53].

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[40] Demand response or demand side management (DSM) refers to deliberate changes in electricity use as a way to adjust the electrical load to better match availability of supply and help balance the grid.

3.2. Modelling Menorca's power system

The power modelling tool *Switch 2.0* is used to achieve the objectives proposed by this study: determining the cost-optimum power system that can meet Menorca's electricity needs in the next decade (2021-2030) while lowering its carbon footprint. It is worth noting, once again, that although the local council – *Consell Insular de Menorca* (CIME) – has proposed some specific goals and targets (Figure 18) for the island's electrical system in the *Estratègia Menorca 2030* (Menorca Roadmap 2030) initiative, they are not, in any way, integrated into the modelling and simulations herein presented. This ensures an objective and independent assessment, motivated by the techno-economic merits of each technology and free of distortions or biases.

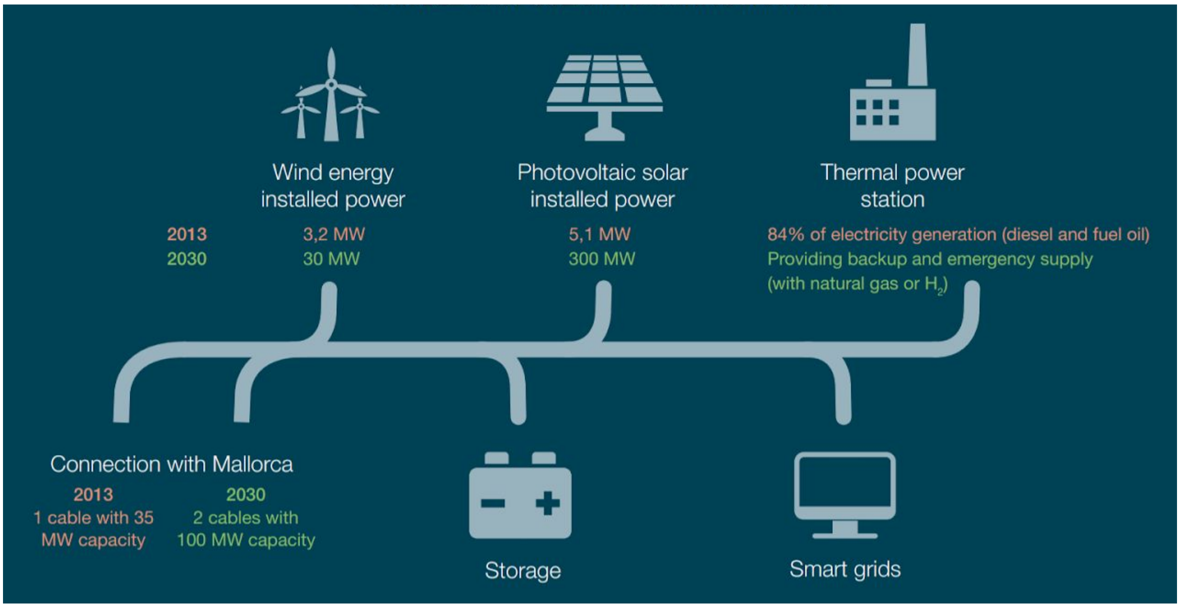

Figure 18 - Electricity system configuration proposed in the *Estratègia Menorca 2030* [54]

The implementation of Menorca's power system modelling in *Switch 2.0* is in detail in the next two sections: *Input Data* (Section 3.2.1.) and *Scenarios* (Section 3.2.2.). Together they make up the entire modelling framework and provide all the information needed to understand the reasoning and limitations of the techno-economic optimization being performed.

3.2.1. Input data

The design and operation of a power system is based on the maxim of balance between supply and demand. Time sensitive data for the operational balance of Menorca's electrical system, such as electricity demand, generator commitment and variable capacity factors (solar irradiation and wind speeds) is collected in hourly[41] intervals from historical databases. The details of each data set is provided in its respective section.

Since the time horizon of the study is a period of ten years (2021-2030) into the future, the historical data is used as a baseline for the forecast of the parameters going forward. The criteria and assumptions for the extrapolation of the data to generate such forecasts shall be clearly stated and explained.

3.2.1.1. Electricity demand

Hourly electricity demand of Menorca for the year of 2019 taken from *Red Eléctrica de España* (REE), the Spanish transmission system operator, is used to establish the baseline for year 2021, the first year considered in the study. It is important to note that the demand data obtained from REE represents the total electricity supply needed to meet Menorca's demand, thus accounting for both consumption and system losses within the island (e.g. transmission, distribution, substations, etc).

Based on the historical trend and projections made by IME, the long-term outlook is approximately 1% growth in demand yearly [37]. However, due to the socio-economic effects of the COVID-19 global pandemic[42] – especially in the tourism and hospitality industries – Menorca is bound to experience a year-over-year (YoY) reduction in electricity demand in 2020. Since 2020 is not part of the time horizon of the study (which begins in 2021), the short-term impact of the pandemic on the island's electricity consumption does not directly impact the model. Hence, considering IME's expected long-term growth of electricity consumption and the temporary effects of the pandemic, it is assumed that Menorca will have the same demand in 2021 as it did in 2019, thus establishing the baseline for the first year of the simulation (Figure 19).

[41] Data sets with lower granularity (e.g. daily, weekly averages) may be used to simplify computational complexity and simulation run times. When this is the case, the exact time interval used will be clearly stated and justified.

[42] The COVID-19 pandemic, also known as the coronavirus pandemic, is a currently ongoing global pandemic of coronavirus disease 2019 (COVID‑19), caused by severe acute respiratory syndrome coronavirus 2 (SARS‑CoV‑2). The outbreak was first identified in Wuhan, China, in December of 2019. The World Health Organization (WHO) declared it a Public Health Emergency of International Concern on January 30th, 2020, and a pandemic on March 11th, 2020. As of June 29th, 2020, more than 10 million cases of COVID-19 have been reported in more than 188 countries and territories, with more than 502,000 deaths having been attributed to the virus [55].

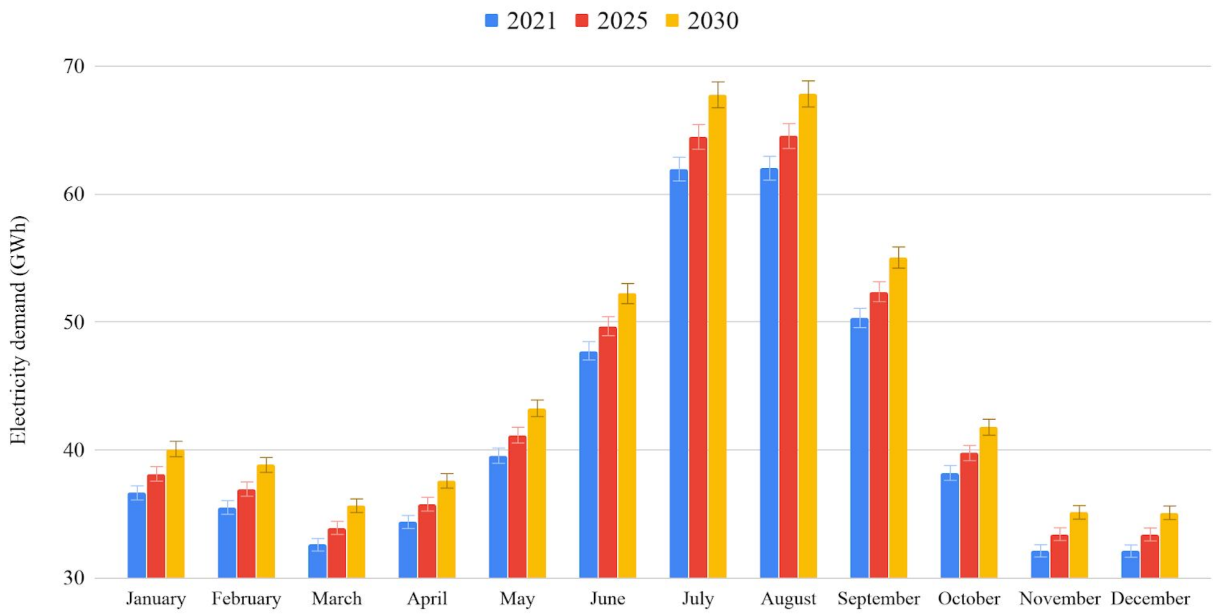

Figure 19 - Menorca's monthly electricity demand based on 1% annual growth forecast (Elaboration: author)

For the nine years of the study that follow, from 2022 to 2030, consumption is increased by 1% uniformly across all data points – based on projections from IME [37] – in addition to a randomization factor within the interval (-1%, 2%)[43] – Figure 20. The randomization factor aims to introduce a stochastic component to the projections of future power demand. Though such growth projections are expected to factor in the gradual electrification of road transportation, as electric vehicles (EVs) gain market share in the coming years, the upwardly skewed randomization interval further adds to the long-term projections in electricity demand to ensure the system can cope with the incremental demand from EVs.

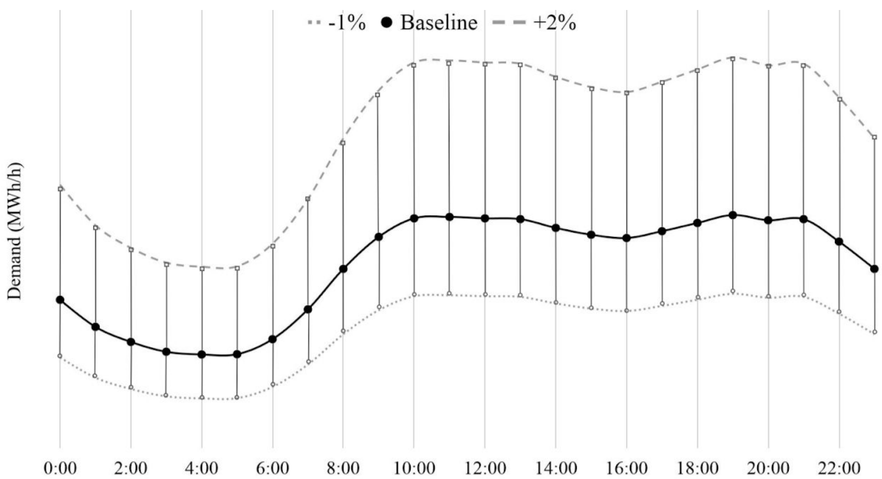

Figure 20 - Randomization interval (-1%, 2%) of hourly demand for a sample day (Elaboration: author)

[43] The asymmetric randomization interval skews the data upwards, consequently creating a safety contingency buffer by slightly oversizing the system.

3.2.1.2. Power technologies

Continuous advances and innovation in the energy industry have significantly lowered costs and improved efficiencies of power generators. Emerging clean and renewable technologies are reaching commercial maturity as steep experience curves and novel manufacturing processes increase their competitiveness. The main examples of such technologies are solar PV, onshore wind and lithium-ion batteries, for which the levelized cost of electricity (LCOE[44]) has come down by 90%, 60% and 85%, respectively, in the last decade [56][57].

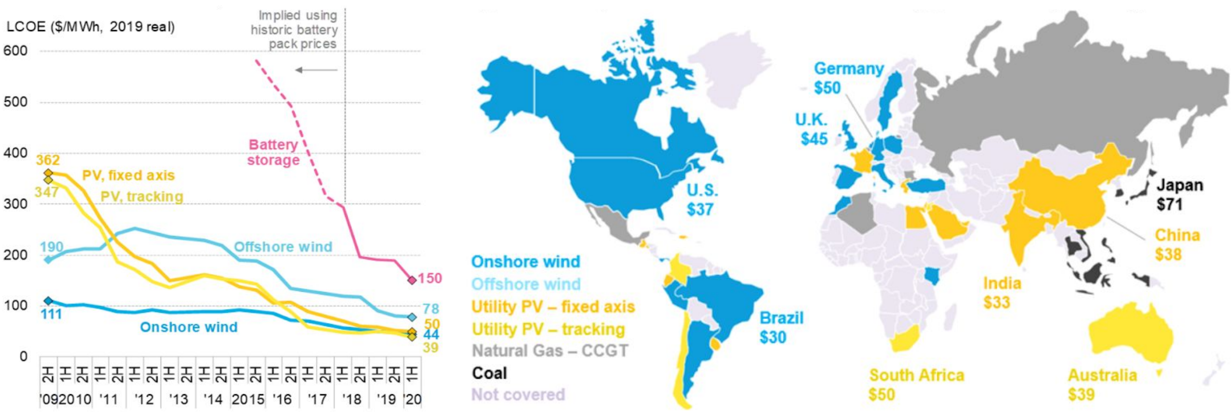

Figure 21 - Global LCOE benchmarks[45] (left). Cheapest source of new bulk electricity generation[46] 1H-2020 (right) [58] (Elaboration: BNEF)

Such significant cost reductions have drastically altered the market dynamics of power generation worldwide, with solar and wind now representing the cheapest source of new-build generation for at least two thirds of the global population, which represents 71% of global GDP (Figure 21–right). In countries such as Australia, China, Chile and the United Arab Emirates – which have favorable weather conditions – new solar photovoltaic and wind energy projects are competitive enough to challenge the existing fleet of fossil fuel power plants [58].

Given the rapidly changing landscape of the energy industry, it is crucial to model all competitive technologies that can be feasibly implemented in Menorca. Table 2 shows a list of the technologies considered in this study and some of the parameters used to model them in the context of Menorca's power system.

[44] LCOE measures the all-in expense of producing one MWh of electricity from a new project, taking into account costs of development, construction and equipment, lifetime, financing, feedstock, operation and maintenance.

[45] The global benchmark done by BNEF is a country weighted-average using the latest annual capacity additions. The storage (battery) LCOE is reflective of utility-scale projects with four-hour duration, including charging costs.

[46] LCOE calculations exclude subsidies or tax-credits. The map shows benchmark LCOE for each country in USD/MWh. CCGT: combined-cycle gas turbine.

Technology	Type	Energy source	Existing capacity (MW)	Min-Max capacity (MW)	Lifetime (years)	Outage rate
Diesel	generator	diesel	224.2	-	20[59]	1.5%[60]
Fuel-oil	generator	fuel-oil	47.4	-	20[59]	1.5%[60]
OCGT	open cycle gas turbine	natural gas	-	10 - ∞	30[61]	2%[62]
CCGT	combined cycle gas turbine	natural gas	-	100 - ∞	30[61]	2%[62]
CCGT-CCS[47]	CCGT with carbon capture	natural gas	-	100 - ∞	30[61]	2%[62]
Solar PV	PV fixed-axis	sun	5.1	2 - 300	25[61]	1%
Wind	onshore turbine	wind	3.2[48]	3.45 - 100	25[61]	3%[63]
Sea-cable Mallorca-Menorca	transmission[49]	HVAC line	35[50]	35 - 105	40[64][65]	2%[66]
Li-ion battery	storage	electro-chemical	-	1 - ∞	15[67]	-

Table 2 - Parameters of power technologies considered to model Menorca's electrical system

It should be noted that all technologies considered (Table 2) are modelled based on utility-scale attributes (large power plants in the megawatt range). Although rooftop residential and commercial solar PV projects are being increasingly adopted by consumers, their higher costs relative to larger utility-sized projects that benefit from economies of scale, makes their consideration immaterial for a centrally planned lowest-cost system.

Therefore, power sources that are not cost competitive with the ones presented in Table 2 and/or cannot be viably implemented at scale due to limited availability of resources in Menorca: coal, offshore wind, municipal solid waste (MSW), biomass and hydrogen; are not considered in this study[51]. Furthermore, mature technologies that are dependent on specific geographical characteristics, such as hydroelectricity, pumped hydro storage (PHS) and geothermal, which cannot be feasibly deployed locally due to the absence of the required conditions are also not considered[52]. Nevertheless, the eventual integration of any such technology to Menorca's power

[47] CCGT-CCS is considered as it may be competitive in a scenario where carbon emissions are priced.
[48] The 3.2 MW of existing wind capacity (Milà plant), built in 2004, is modelled to be retired no later than 2028.
[49] Since the sea-cable allows electricity generated outside of Menorca to be brought into Menorca, it is abstracted and modelled together with generators, unlike transmission lines internal to the island.
[50] Though the cable has a capacity of 100 MW, operation is capped around 35 MW due to technical requirements.
[51] Diesel and fuel-oil are only considered due to the existing installed capacity in Menorca (GESA power plant).
[52] The high costs of creating the required conditions for deployment make these technologies uncompetitive, while adding unnecessary computational complexity to the optimization process. (This also applies to nuclear power).

system would not invalidate or conflict with the model presented in this study, and should be regarded as additional capacity that adds robustness and strengthens reliability.

Switch 2.0 models each power generating technology according to certain characteristics defined by the user. Table 2 includes a few of them: type, fuel (e.g. diesel, natural gas, etc) or non-fuel resources (e.g. sun, wind, etc); existing capacity; lifetime; outage rate (time used for both scheduled and possibly forced or unplanned maintenance); and other optional parameters such as the maximum or minimum capacity allowed. A minimum is applied to generators based on the unit size of commercially available machines, while a maximum is applied to solar PV, wind power and to the submarine interconnection between Mallorca and Menorca based on plans disclosed by IME and REE (who is responsible for transmission projects in Spain) [68][69].

3.2.1.3. Costs: CAPEX, OPEX and fuel

In addition to the parameters listed in Table 2, several cost variables are used by *Switch 2.0* for each technology; after all, the purpose of the model is to identify the lowest-cost power system capable of meeting the projected demand. Table 3 shows the cost inputs of each technology for the current year (2020) as well as the expected CAPEX reductions for the next ten years.

Generation						
Technology	**CAPEX (€/MW_{AC})**	**$OPEX_{fixed}$ (€/MW_{AC}-year)**	**$OPEX_{variable}$ (€/MWh)**	**Fuel[53] (€/MWh_{el})**	**CAPEX[54] (2020-2030)**	**Efficiency (electrical)**
Diesel	590,909[59][60]	22,727[59][60]	-	349.12[70][71]	-	33%[37][59][74]
Fuel-oil				106.24[70][71]	-	33%[37]
OCGT	728,182[61][75][76][77]	13,989[61][75][76][77]	7.26[75][76][77]	93.13[72]	-8%[77]	38%[75][76]
CCGT	997,273[61][76][77][78]	13,830[61][76][77][78]	2.61[76][77][78]	65.40[72]	-9%[77]	55%[76][78]
CCGT-CCS	2,206,364[77][78]	27,945[77][78]	5.83[77][78]	73.50[72]	-15%[77]	48%[78]
Solar PV (fixed-axis)	875,455[61][76][77]	17,189[61][76][77]	-	-	-24%[77]	-
Wind (onshore)	1,509,545[61][76][77][78]	31,755[61][76][77][78]	-	-	-24%[77]	-
Sea-cable Mallorca-Menorca	2,400,000[79][80]	60,000[81]	-	58.12[73]	-	97%[82]

[53] Average prices for the last 5 years for Spain as reported in the European Commission's fuel price bulletins, including taxes and levies [70][71][72]. *Sea-cable*: average Balearic demand price 2015-2019 (inclusive) [73].
[54] The CAPEX reductions expected from 2020 to 2030 are annualized evenly. Investment decisions are evaluated by *Switch 2.0* in the beginning of each year of the study (2021-2030) based on adjusted costs for each technology.

Storage						
Technology	**CAPEX[55] (€/MW$_{AC}$)**	**OPEX (€/MW$_{AC}$-year)**	**Expansion cost (€/MWh)**	**Storage duration[56] (h)**	**CAPEX (2020-2030)**	**Efficiency**
Li-ion battery	1,358,182[77][84]	33,955[77]	340,455[67][77]	4	-40%[67]	85%[67] (round-trip)
	852,576[77][84]	21,314[77]	401,364[77][84]	2		
	595,000[77][84]	14,875[77]	473,182[77][84]	1		

Table 3 - Costs and efficiency of power technologies considered to model Menorca's electrical system

Although diesel and fuel-oil generators are modelled with the same CAPEX and OPEX (Table 3), these cost approximations do not significantly affect the model since it is simply intended to represent the existing capacity at the GESA power plant in Mahón, Menorca. These existing diesel and fuel-oil generators are expected to be retired in the next 3 years due to their age (already more than 25 years old), and high emission of NOx, SOx and particulate matter (PM), which is increasingly at odds with tightening European legislation on air pollution and the demands of local citizens. Thus, neither diesel nor fuel-oil generators are considered for new capacity deployment, with their implementation done strictly for purposes of the operation of the existing capacity, until its retirement, modelled to take place no later than 2023.

Both CAPEX and OPEX are calculated as an average of the cited references[57], and the expected CAPEX reduction by 2030 is annualized and proportionately applied to the respective OPEX of future projects. Prices for diesel, fuel-oil and natural gas (oil-derived fuels) are taken as the average of the last 5 years for Spain based on bulletins issued by the *European Commission*, including taxes and levies. As an international commodity, oil prices are constantly fluctuating depending on market conditions and investors' expectations. This stochastic behavior makes predicting future prices – especially over a ten-year period – an unfeasible task. Forecasting fossil fuel prices based on historical data or price trends is, in no way, guaranteed to produce a higher level of accuracy[58] for projected prices [85][86]. Hence the modelled scenarios (Section 3.2.2.) include a sensitivity analysis to account for the cost of hedging fuel prices to mitigate market instability.

[55] Calculation: CAPEX ($/MW) = {battery pack cost ($/MWh) x storage duration (hours)} + BOS ($/MW) [83].
[56] How many hours to discharge the battery at its rated power, or its energy-to-power ratio (MWh/MW).
[57] Where applicable, an exchange rate of EUR/USD of 1.10 is used to convert costs from U.S. dollars to euros.
[58] The difficulty of accurately predicting future market behavior and prices (even for well-known technologies such as solar PV) is a significant source of uncertainty (and error) when forecasting and modelling energy systems.

Since the submarine interconnection between Mallorca and Menorca is being modelled as a generator, the cost of the electricity transmitted through it must be accounted for so the optimization can appropriately identify the lowest-cost system. The price for the electricity imported via the sea-cable Mallorca-Menorca is calculated based on the average demand price of the last five years for the Balearic Islands, as reported by the *Sistema de Información del Operador del Sistema* (*ESIOS*), the TSO's information system. It should be noted that, despite being connected to the Iberian Peninsula through the HVDC submarine cable running between Mallorca and Valencia, all four Balearic Islands are considered a non-peninsular electrical system (i.e. *sistema no peninsular* or *SNP*), with a different market price for electricity than the Spanish Peninsula.

For storage technologies – represented in this study by lithium-ion batteries – *Switch 2.0* considers both the charging and discharging effects on the power system. Aside from the round-trip efficiency (Table 3), the storage technology's behavior is characterized by two parameters: the *energy-to-power ratio*, which relates the amount of energy stored in the battery to its rated power; and the *energy release rate*, a measure of how fast energy can flow into and out of the battery (i.e. power). The former is shown in Table 2, with 4-hour, 2-hour and 1-hour batteries modelled for this study; while the latter is considered to be 1 for all batteries, meaning they can be charged and discharged at 100% of their rated power[59].

It is not uncommon to assign a cost to an unserved unit of electrical load when modelling power systems; in other words, a penalty price for not meeting demand. However, because *Switch 2.0* constructs an intrinsically constrained model in which the electrical demand being simulated must be met at all times, no such cost is introduced for this study.

3.2.1.4. Non-fuel energy sources

In addition to the fuel-based power generators considered for Menorca's power system model, there are also the technologies based on other (non-fuel) energy sources; namely solar PV and wind energy (Table 2). In order to integrate them to the model, their power generation potential is calculated based on the expected local weather conditions: solar irradiance and wind speeds, respectively, which are then converted to a time varying capacity factor[60].

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[59] The battery's rated power is a decision variable to be determined by the optimization algorithm.
[60] The efficiency parameter, absent for solar and wind (Table 3), is replaced by a variable capacity factor.

Historical solar irradiance data is taken from the *European Photovoltaic Geographical Information Systems* (PVGIS Europe) [87]. More specifically, the database PVGIS-SARAH is used to obtain hourly solar irradiance for Menorca based on the average from 2005 to 2016, the latest available year (Table 4).

Menorca: PVGIS Europe Weather Data	
Database	PVGIS-SARAH[61]
Type	Satellite
Years	2005-2016
Data granularity	Hourly
Location	Menorca, Spain
Coordinates	40° North, 4° East
Elevation	128 m
Optimum slope (solar panel tilt)	36° South
System losses (DC-AC)	0%
Wind speed height	10 m

Table 4 - PVGIS Europe weather data used to model solar PV and wind energy potential [87]

Because the CAPEX and OPEX for solar PV projects are calculated in EUR/MW_{AC} (Table 3), DC-to-AC conversion losses are already incorporated into the costs[62]. Solar PV hourly electricity generation potential is calculated as a function of the local solar irradiance in relation to standard test conditions (STC) by which solar modules are rated (1000 W/m^2 and 25°C) [88]. The irradiance is implemented as a variable (hourly) capacity factor that scales a solar project's output in relation to its rated peak capacity. A randomization factor in the interval (-3%, +3%) is applied to every datapoint to reflect variations in the hourly solar irradiance during the 10-year study period (2021-2030).

The scaling factor generated by PVGIS is based on crystalline silicon (c-Si) solar modules in a fixed-axis configuration and mounted at the optimum slope of 36° south (Table 4) [89]. The resulting annual capacity factor used as the baseline (before the randomization) is 26.3%. Figure 22 shows the hourly capacity factor for the solstice and equinox days.

[61] This data set has been calculated by CM SAF and the PVGIS team. This data covers Europe, Africa, most of Asia, and parts of South America [88].
[62] Additional system losses of 15% are considered for the existing 5.1 MW of installed solar capacity based on historical data [37]. The power plants started operation in 2008, and thus possess lower efficiency than the current state-of-the-art for solar photovoltaic.

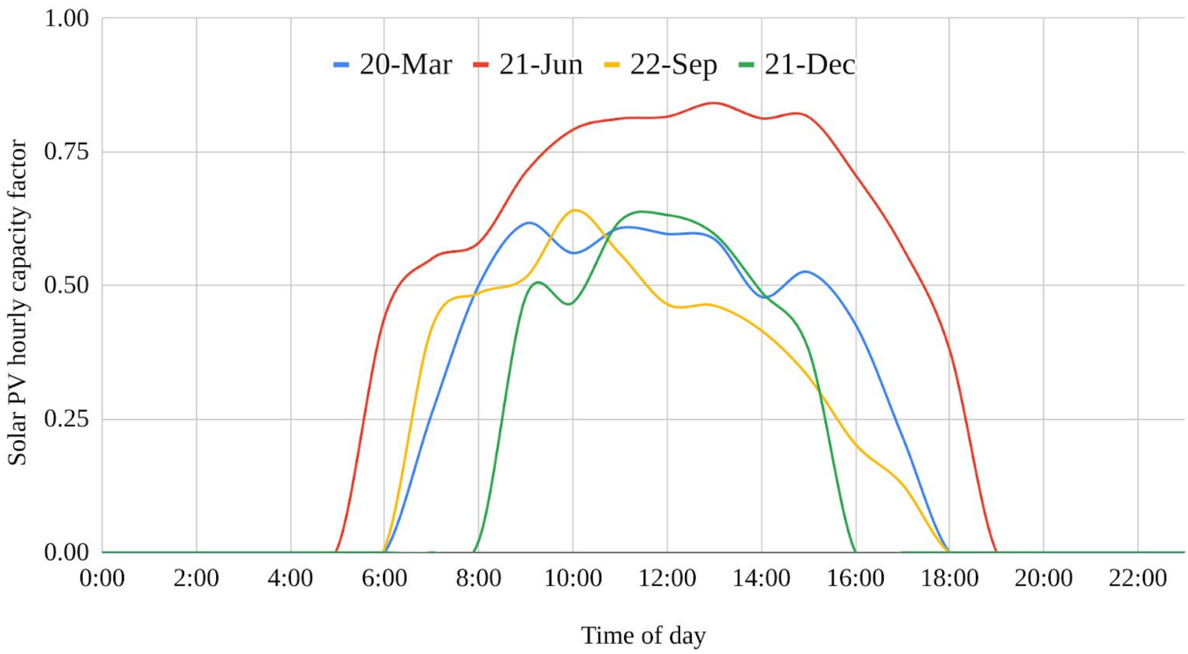

Figure 22 - Solar hourly capacity factor baseline for solstice and equinox days of 2021 (Elaboration: author)

Figure 22 only shows the solar PV hourly capacity factor for four sample days[63]. Variations in solar irradiance are expected both intraday and throughout the seasons, primarily due to changes in local weather conditions such as cloud coverage and rainfall.

Similarly, for wind energy projects, the parameter used to calculate the generation potential is the wind speed. Data obtained from PVGIS Europe, using the geographical parameters described in Table 4, is used to estimate hourly wind speeds in Menorca for the 10-year period being modelled (2021-2030).

Unlike solar irradiance, which varies mostly intraday; wind patterns tend to present a seasonal behavior that can be drastically affected by factors such as ocean streams, air temperature and surface roughness[64]. This makes estimating and predicting the wind especially challenging. One commonly used statistical method for modelling wind speeds is the *Rayleigh distribution*[65]. It is dependent on a single parameter: the local mean wind speed. Equation 4 shows the Rayleigh probability density function of wind speed (v) in terms of its mean value ($\overline{v}$) [91][92].

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[63] The deliberate choice to display four days in Figure 22 is made to avoid an excessive number of data points that would impact the clarity of the visual representation of the graph.

[64] In the lower layers of the atmosphere (below 1 km), wind speeds are affected by the friction against the surface of the earth. In the wind energy industry, the distinction between the roughness of the terrain, the influence from obstacles and the influence from the terrain contours, is referred to as the orography of the area [90].

[65] Rayleigh distribution is a special form of *Weibull distribution* in which the shape parameter (k) is equal to 2 [91].

$$f(v) = \frac{\pi v}{2\overline{v}^2}\ exp\ \left[-\frac{\pi}{4}\left(\frac{v}{\overline{v}}\right)^2\right] \qquad \text{(Equation 4)}$$

where $f(v)$ is the probability of wind speed v occurring; and $\overline{v}$ is the local mean wind speed. In order to evaluate the applicability of the Rayleigh distribution function to Menorca's weather, a histogram of local hourly wind speeds from 2005 to 2016 (with more than 105,000 data points) is created using the PVGIS-SARAH database (Table 4) and plotted together with the respective Rayleigh distribution ($\overline{v} = 5.65\ m/s$. Figure 23 shows a noticeable correlation between the empirical wind speed readings and the Rayleigh probability function curve.

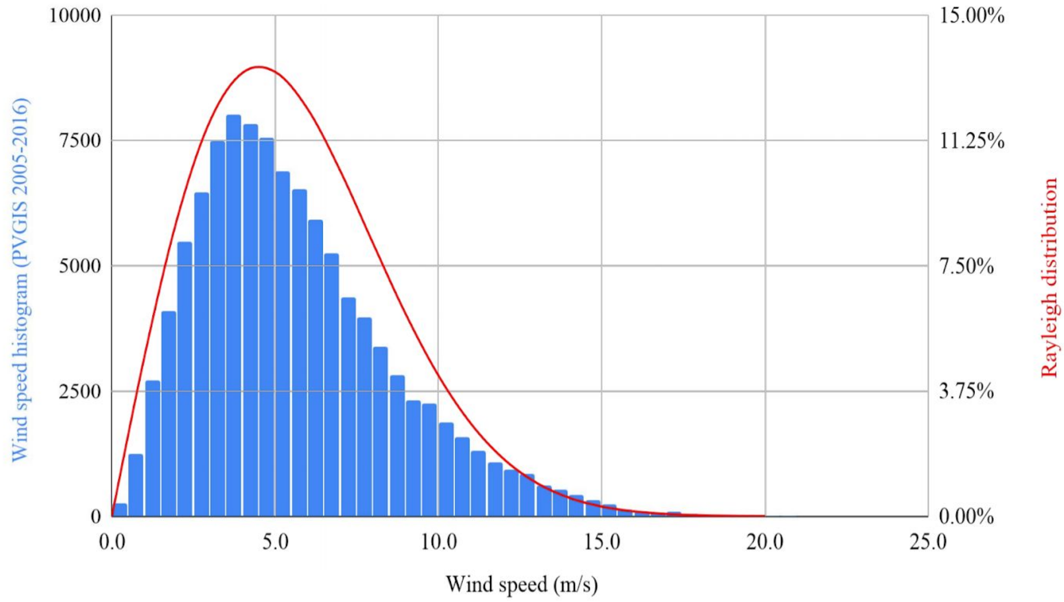

Figure 23 - Menorca's wind speed histogram (2005-2016) and Rayleigh distribution (Elaboration: author)

The wind speed data set used to calculate Menorca's wind energy potential is the 2019 hourly measurements from the island's airport[66], captured at a height of 10 meters [93]. The data points are adjusted by a randomization factor from the interval (-10%, +10%). The aim of the randomization is to introduce variability to the historical data, allowing for a more stochastic and thus realistic analysis.

The wind speeds need to be converted into energy potential. In other words, given the estimated hourly wind speeds, the amount of electricity that can be generated by a wind turbine must be calculated so that the contribution of wind energy projects to Menorca's power system can be appropriately modelled.

[66] Mahón airport - IATA: MAH; ICAO: LEMH.

Optimized for sites with low- and medium-wind speeds – such as Menorca – the *Vestas V136-3.45* turbine is used to calculate the wind energy potential of the island[67] (Figure 24) [94].

Vestas V136-3.45	
Rated power	3.45 MW
Cut-in wind speed	3 m/s
Cut-out wind speed	22.5 m/s
Re cut-in wind speed	20 m/s
Wind class	IEC IIIA/IEC IIB
Rotor diameter	136 m
Swept area	14,527 m^2
Hub height	82 m
Blades	3
Blade length	66.7 m

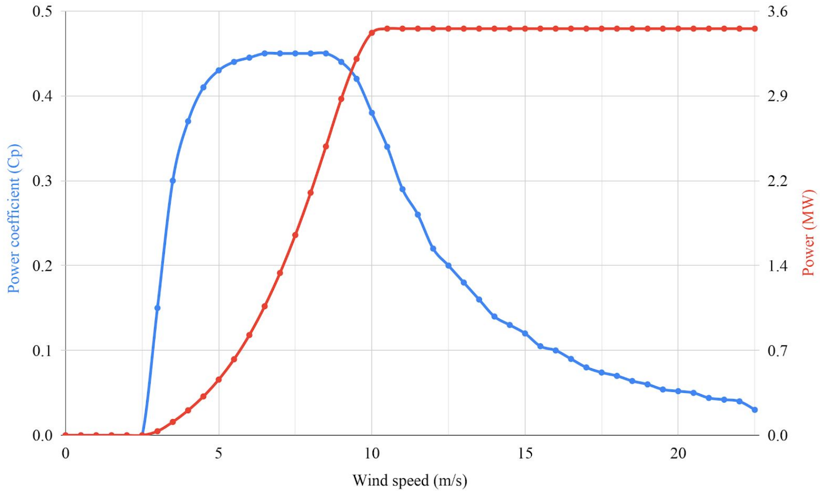

Figure 24 - Vestas V136-3.45 technical specifications (left) and power curve (right) [94][95] (Elaboration: author)

In addition, the wind speeds, thus far only parametrized for a height of 10 meters, must be adjusted for the height of the *Vestas V136-3.45* hub so that the available wind energy can be appropriately determined. The wind logarithmic law provides a simple relationship between wind speeds at different heights, as described in Equation 5 [96]:

$$v_z = v_{ref} \frac{ln(\frac{z}{z_0})}{ln(\frac{z_{ref}}{z_0})} \qquad \text{(Equation 5)}$$

where v_z is the wind speed at a given height z; while v_{ref} is the wind speed at the reference height z_{ref}; and z_0 is the local roughness length[68]. A roughness length of 0.05 is used for Menorca given the prevalence of open agricultural and natural areas, few and scattered buildings and softly rounded hills [98]. Hence, Equation 5 allows for the entire wind speed data set for a height of 10 meters to be adjusted to the hub level of the *Vestas V136-3.45* turbine, 82 meters.

The energy carried by the wind at hub height must be determined before calculating the turbine's output based on its power coefficient curve.

[67] Based on historical data, additional losses of 25% are considered for the 3.2 MW of installed capacity at the Milà wind farm [37]. The plant, which started operation in 2004, has much less efficient turbines than the *V136-3.45*.
[68] Surface roughness length is a property of the surface which can be used to determine the way the horizontal wind speed varies with height. The wind speed at a given height decreases with increasing surface roughness [97].

$$P_w = \frac{1}{2}\,\rho\, A\, v^3 \qquad \text{Equation 6}$$

Derived from the basic kinetic energy formula ($E_k = \frac{1}{2} mv^2$), Equation 6 is used to calculate the wind power crossing the turbine P_w; where ρ is the air density, A is the area swept by the turbine's blades and v is the wind speed. Because the wind power (P_w) cannot be fully extracted by the turbine due to efficiency losses[69], the turbine's power output P_t is dependent on its power coefficient C_p, and is determined as shown in Equation 7.

$$P_t = P_w\, C_p \qquad \text{Equation 7}$$

Finally, the hourly capacity factor to be used by *Switch 2.0* to model the wind energy potential in Menorca can be calculated as the ratio between a turbine's power output at a given hour P_t and its rated capacity of 3.45 MW. Figure 25 shows the 10-day trailing average capacity factor for 2021, the first of the ten years modelled[70].

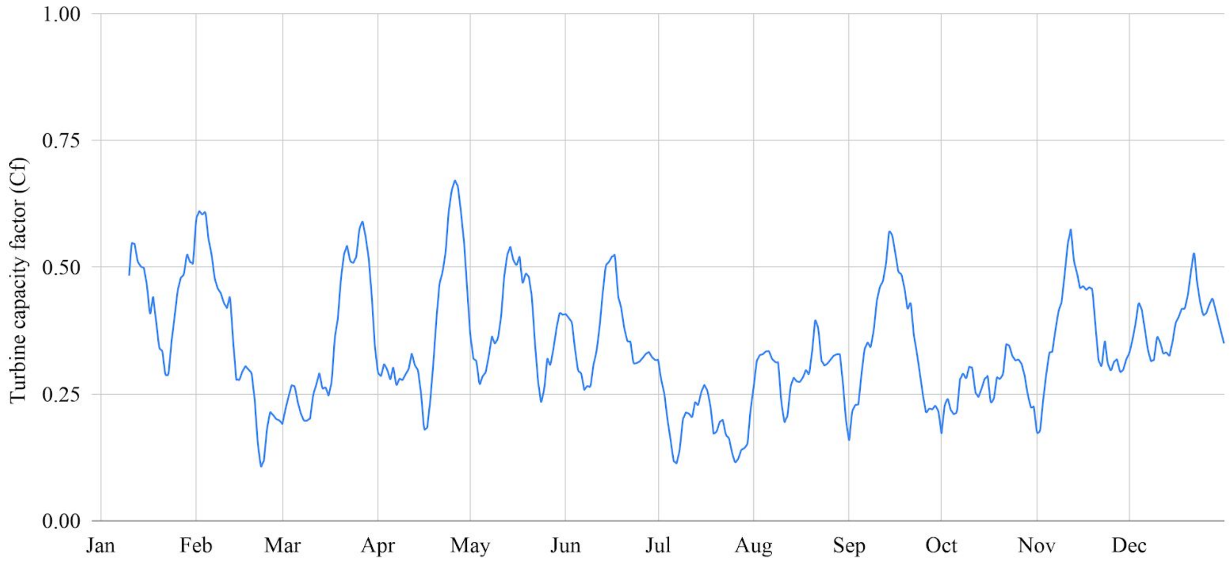

Figure 25 - Modelled 10-day trailing average wind turbine capacity factor for 2021 (Elaboration: author)

Despite an annual average capacity factor of 34%, the high variance of wind speeds causes significant changes to the daily and weekly wind energy output (Figure 25). A modest seasonal pattern can be observed, with lower capacity factors in the summer – a relevant observation given it is the time of year with the highest demand for electricity in Menorca (tourism season).

[69] The theoretical maximum efficiency of a wind turbine, given by the *Betz limit*, is 59.3% (or 16/27) [99].
[70] Recall that a randomization factor is introduced for the following years of the study, out to 2030.

3.2.1.5. Temporal resolution

As described in section 3.1.2., *Switch 2.0* uses three different temporal parameters to model a power system: *periods*, *timeseries* and *timepoints*. Together they can scale both supply and demand of electricity throughout the time horizon being modelled. Thus, Menorca's power system is modelled based on a 3-layer structure covering the 10-year period from 2021 to 2030.

The layer with the highest granularity (i.e. resolution) is the *timepoints* one. These are time intervals used by *Switch* to make operational decisions such as generator dispatch and load balancing. At a higher level, on top, is the *timeseries* layer. Each *timeseries* is formed by a collection of sequential *timepoints*, which *Switch* models circularly, as if the last *timepoint* leads back to the first one within the same *timeseries* [100]. This is done so that the *timepoints* dataset can be scaled to the appropriate temporal resolution represented by the *timeseries* while maintaining a sequential chronology. Finally, the *timeseries* layer is scaled to form *periods*, the highest level (with the lowest granularity) of the three layers. A structural diagram with the temporal resolution chosen for this study is shown in Figure 26.

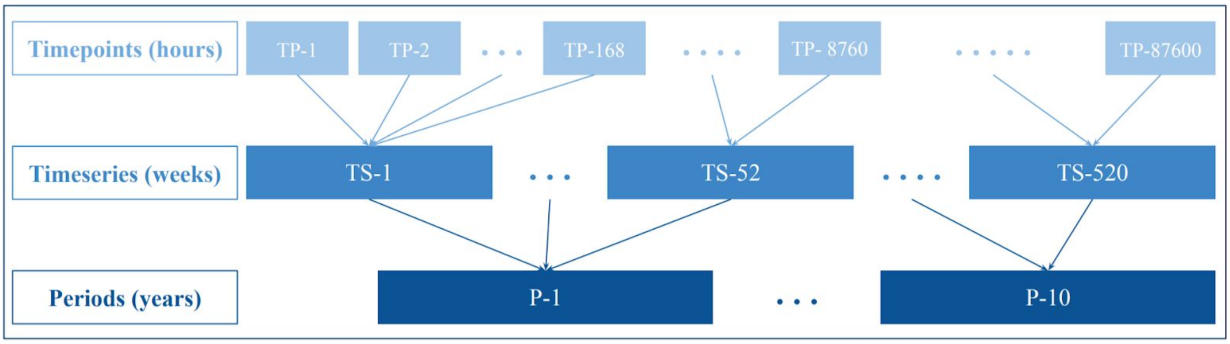

Figure 26 - Temporal structure used to model Menorca's power system in *Switch 2.0* (Elaboration: author)

This rather fragmented temporal structure may be better understood with a practical example of its application in the context of Menorca's power system. First, it shall be noted that although input parameters for electricity demand and the variable capacity factors for solar and wind energy are obtained on an hourly basis, they are actually implemented in the model as 7-day hourly averages. In other words, each week is represented by one day as a single set of 24 *timepoints*[71] (i.e. hourly data points), calculated based on a 7-day trailing average[72].

[71] Daylight savings are eliminated to normalize all days to 24 hours.

[72] The granularity of the model is lowered to simplify the computational complexity of the optimization, which could otherwise not be performed successfully with the computing resources available to the author (insufficient memory and processing power, especially for multithreading the computer's CPU).

Therefore, in this study, a single *timeseries* only has 24 data points of input data assigned to it, despite representing an entire week (168 hourly data points) in the model's time horizon. In order to adjust for this discrepancy in temporal resolution, the 24 sequential data points (i.e. *timepoints*) in each *timeseries* representing a single (average) day, are simulated 7 times circularly, adding up to a total of 168 data points per *timeseries*, the equivalent of one full week.

Finally, the *timeseries* (scaled to represent an entire week with 168 *timepoints*), are modelled sequentially to the temporal resolution of a *period*, in this case one year. Given that the total time horizon of the model is ten years (2021-2030), each year is modelled as having 52 weeks, for a total of 520 weekly *timeseries* corresponding to 10 annual *periods*.

Note that the use of a 52-week year is an approximation, since it only amounts to a total of 364 days (8,736 hours) per year, and not the actual 365 days (8,760 hours) in a typical non-leap[73] year. Nevertheless, this approximation does not materially impact the results of the study as, in addition to being negligible (less than 0.3% difference), the model is designed to be continually operational to meet Menorca's expected daily electricity demand (day in, day out).

3.2.1.6. Transmission

Transmission capacities represent an important parameter when modelling power systems as they may constraint the dispatch of generation assets based on how much power can flow through each node of the electrical network.

As a relatively small island of about 700 km^2, Menorca stretches 47 km wide between its two biggest and most populous municipalities: Mahón and Ciutadellla – the maximum distance between two points on the island. Since the GESA thermal power plant, located in Mahón, is currently the single main source of electricity in Menorca, its generation must flow across the island through transmission and distribution lines before reaching final consumers (Figure 12).

This centralized power generation structure requires transmission assets to be able to flow enough electricity to meet demand in all 8 municipalities. Thus, Menorca's transmission network is implemented in *Switch 2.0* as a copperplate model with a single zone. This implies generation dispatch is not constrained by transmission limitations and costs are homogeneous[74].

[73] The leap years 2024 and 2028, which are part of the study's time horizon, are modelled as having only 365 days.
[74] Modelled as a single zone without transmission bottlenecks, the system's marginal generation cost is uniform.

3.2.1.7. Carbon emissions

In order to properly assess the carbon footprint of the modelled power system, emissions from different fuels must be calculated based on the dispatch of fossil-based generators. Table 5 shows the carbon emissions[75] – on an energy basis – for each of the fossil fuels considered, namely: diesel, fuel-oil and natural gas.

Fuel	kg-CO_2/GJ_{fuel}	kg-CO_2/kWh_{fuel}
Diesel	74.1	0.27
Fuel-oil	77.4	0.28
Natural gas	56.1	0.20

Table 5 - Carbon emissions (energy basis) for fossil fuels modelled [101]

Furthermore, the carbon intensity per unit of electricity for each fossil-based generator is dependent on both its efficiency and the fuel used. Figure 27 shows the emissions per kilowatt-hour of electricity for each of them. The submarine interconnection between Menorca and Mallorca is modelled based on Spain's 2019 electricity-related carbon intensity – 192 grams of CO_2 per kilowatt-hour of electricity – and considering transmission losses of 5%[76].

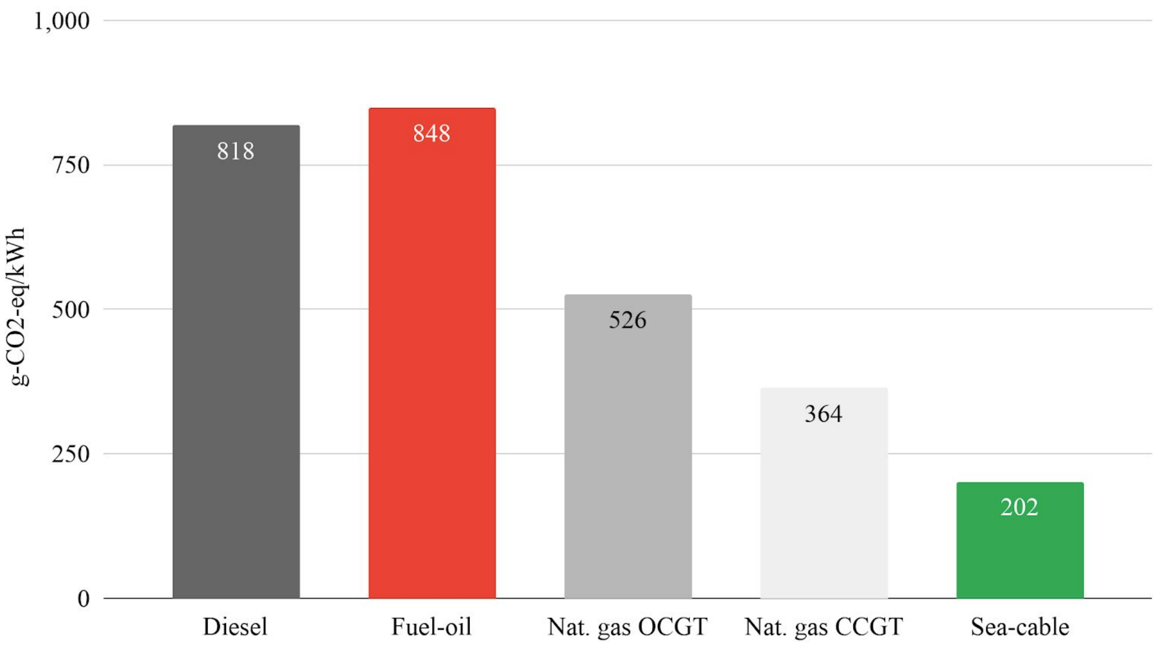

Figure 27 - Carbon emissions per unit of electricity for fuel-based generators[77] (Elaboration: author)

[75] Excluding upstream carbon emissions from fuel production (i.e. only combustion-related emissions).
[76] A 95% transmission efficiency from the peninsular system to Menorca (through Mallorca) is considered [82].
[77] OCGT: open cycle (natural) gas turbine; CCGT: combined cycle (natural) gas turbine.

3.2.1.8. Financials

As a techno-economic analysis of Menorca's power system, this study aims to quantitatively identify the mix of technologies that can reliably meet demand in a cost-optimum fashion. Hence, the optimization of the model is done in terms of the costs of the system with the goal of minimizing the net present value (NPV) of all investments and expenditures from 2021 to 2030.

In order to calculate the NPV, costs that are incurred in the future must be discounted to their present value by means of a discount rate (Equation 2), a measure of the opportunity cost of allocating capital to a project (i.e. time value of money). In addition, all capital costs are amortized over the life of each project using an interest rate[78] [100][102]. Table 6 shows the financing input parameters used by the cost-optimization algorithm.

Financial parameters[79]	
Base year	2021
Interest rate	5%
Discount rate	2%
Investment decisions (CAPEX)	Beginning of every year (2021-2030)

Table 6 - Financial parameters used for the NPV-based cost optimization in *Switch 2.0*

3.2.2. Scenarios

The numerous variables and parameters involved in the modelling of a power system over a period of 10 years, combined with the stochastic nature of weather phenomena and human behavior, represent a significant challenge to the precision of the final results. Assumptions and forecasts ought to contain inaccuracies due to future uncertainties, for example, in regards to fuel prices, electricity demand, market conditions and eventual climate policies.

In an attempt to assess some of the future uncertainties around these variables and their effect on the techno-economic optimization of Menorca's power system, three scenarios (in addition to the base case model) are implemented and simulated and their results analyzed and compared.

[78] For further clarification: the interest rate is the cost of the capital considered for investments (e.g. loan interest); whereas the discount rate is the opportunity cost of the invested capital (annual real discount rate used to convert future dollars to present) [103].
[79] References used for the discount and interest rates: [104][105]. Nonetheless, the author's own discretion is used to adjust the parameters to more accurately reflect current market conditions. For context, the yield on Spain's 10-year sovereign bond is 0.41% at the time of writing (July 10th, 2020) [106].

The main goal is to use the additional scenarios to deliberately vary specific parameters of the model and assess their impact on the results. A sensitivity analysis is performed for policy-related externalities: a carbon pricing scheme and renewable portfolio standards (RPS); as well as for the cost of hedging fuel (natural gas) prices to mitigate eventual market fluctuations. Together, the three scenarios combine the introduction of the following input parameters to the model:

- *Carbon pricing*: introduction of a carbon price (in euros per tonne of CO_2) that affects cost of dispatching generators based on their respective carbon emissions;
- *Renewable portfolio standards (RPS)*: implementation of a renewable energy mandate as a percentage of total electricity generation[80] to be met by 2030;
- *Natural gas price hedging*: sensitivity analysis to evaluate how the different costs of hedging natural gas prices impact the optimization results;

Table 7 summarizes the three different scenarios considered.

Scenario	**Carbon price**	**RPS**	**Fuel price hedge**
Base case	-	-	-
#1	✓	-	-
#2	-	✓	-
#3	-	-	✓
	(✓) Included	(-) Not included	

Table 7 - Sensitivity analysis conducted for each of the 3 scenarios modelled and simulated

3.2.2.1. Base case scenario

The base case scenario is implemented and simulated using the default parameters and input data described in the *Input data* section (3.2.1). It is devoid of the externalities presented in the other three scenarios, serving as a baseline model and benchmark for comparison purposes.

3.2.2.2. Scenario 1 - Carbon pricing

The first (alternative) scenario presents an analysis of how different levels of carbon pricing affect the generation mix of a cost-optimized power system for Menorca. No other input parameter is changed and the model is simulated for the aforementioned time horizon of ten

[80] The introduction of an RPS scenario is especially relevant given the goal of 85% renewable electricity generation by 2030 proposed by CIME (local government) as part of the *Menorca Roadmap 2030* plan [107].

years from 2021 to 2030, with constant prices for fuels: diesel, fuel-oil and natural gas (Table 3). Hence, fuel-based generators are sensitive to carbon pricing schemes in proportion to their respective emissions per unit of electricity generated (Figure 27). The levels of carbon pricing simulated for the sensitivity analysis are: €0, €20, €50, €80 and €100 per tonne of carbon emitted.

3.2.2.3. Scenario 2 - Renewable portfolio standards (RPS)

The second scenario includes no carbon price, so generators do not incur any extra cost due to emissions. However, it introduces an RPS sensitivity analysis in an attempt to demonstrate how government imposed renewable mandates and targets affect the mix of electricity generation of a cost-optimum power system for Menorca. The RPS targets simulated are: 75%, 85% and 95%, all required to be met by the end of 2030.

3.2.2.4. Scenario 3 - Natural gas price hedging

Finally, the last alternative scenario attempts to better represent future variations in the price of natural gas (the main fossil fuel considered in the study) by analyzing how the cost of hedging exposure to market fluctuations impact the optimization results. As is the case with most internationally traded commodities (e.g. oil, gold, wheat, etc), different financial instruments, such as *swaps* and *options*, are available for hedging natural gas exposure. These are normally structured and priced based on market expectations of future supply and demand (e.g. *Dutch TTF Natural Gas Futures*) [108].

This study does not include a detailed analysis or implementation of such hedging mechanisms. Instead, the costs associated with mitigating exposure to future variations in natural gas prices is simply implemented as a percentage of total annual fuel expenditures of gas power plants. Therefore, for this scenario, the sensitivity analysis is constructed from the techno-economic optimization of the model with different annual costs for hedging natural gas prices.

It is important to emphasize that the scenarios (Table 7) are implemented in a complimentary fashion, with the base case representing the foundational model of the study, thereby establishing a frame of reference against which the other three scenarios can be analyzed and interpreted.

4. Results

In order to better understand and contextualize the results of the techno-economic optimization of Menorca's power system, it is important to review the island's current mix of generating capacity and the demand profile based on the electricity consumption of 2019 – which is also used as the baseline for the 10-year study period ranging from 2021 to 2030.

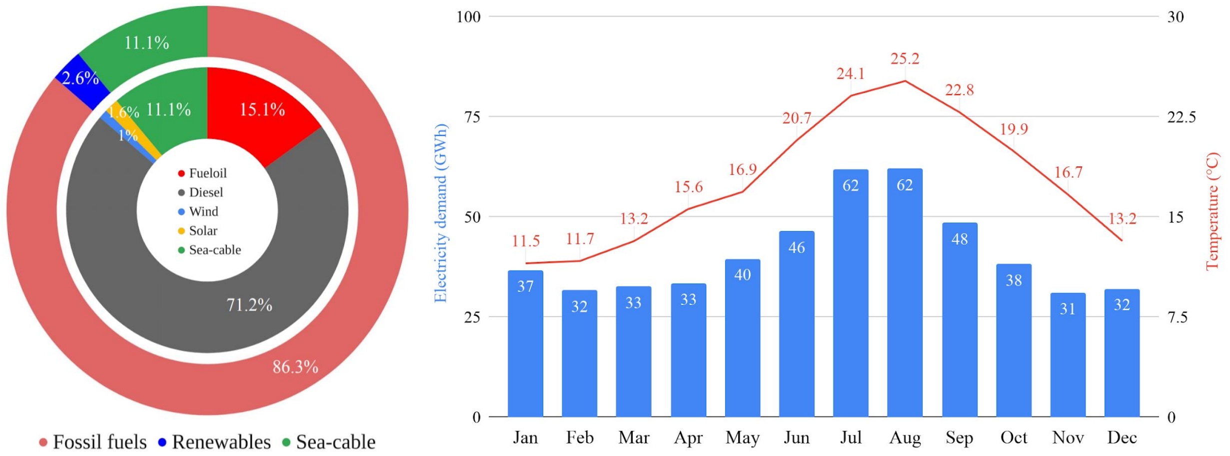

Figure 28 - Power generation capacity mix, 2020 (left). Electricity demand for 2019 and average temperature (right) (Elaboration: author)

Figure 28–left shows how Menorca's power generation capacity is still very much reliant on fossil fuels, with fuel-oil and diesel making up more than 85% of the 315 MW of total installed capacity[81]. Such technology mix is consistent with the fact that, until 2019, less than 3% of the island's annual electricity demand was met by renewables. Figure 28–right highlights the seasonal correlation between electricity consumption and local air temperatures. Aside from the additional demand for cooling (i.e. air conditioning), the high seasonal variability is further exacerbated by the significant influx of tourists during the summer months (high season).

Against this backdrop and the contextual information provided in the previous sections, the results of the techno-economic optimizations can be presented and interpreted in detail. It must be noted that for simulations and scenarios in which input parameters differ from the default values (Table 8), a reasonable explanation shall be provided to justify the changes. As a reminder, the goal of this study is to objectively identify the lowest-cost power system that can reliably supply Menorca with electricity from 2021 to 2030, while taking into consideration the specific characteristics and merits of each technology evaluated.

[81] Considering the sea-cable's operational capacity of 35 MW (not its physical upper limit of 100 MW).

4.1. Base case scenario

The base case scenario represents the simplest analysis that will serve as the baseline for the other scenarios to be interpreted against. It is implemented as a techno-economic optimization based solely on dispatch requirements (balancing supply and demand), natural resources availability (solar irradiation and wind speeds) and the cost of each technology. Table 8 summarizes the input characteristics of the base case scenario.

Parameter	Base case implementation (2021-2030)
Electricity demand	1% annual growth plus hourly randomization (-1%, +2%) - Section 3.2.1.1.
Fuel costs	Constant price: average of the last 5 years (incl. levies and taxes) - Table 3
Sea-cable electricity	Constant price: average Balearic demand price of the last 5 years - Table 3
Non-fuel sources	Randomization: solar irradiation (±3%), wind speeds (±10%) - Section 3.2.1.4.
Financials	Interest rate: 5% and discount rate: 2% - Table 6
Carbon price	N/A
RPS	N/A
Fuel price hedge	N/A

Table 8 - Default input parameters for techno-economic optimization of Menorca's power system

4.1.1. Installed capacity

Figure 29 shows the evolution of Menorca's generation mix from its current state (2020) throughout the period for which the techno-economic optimization is simulated (2021-2030).

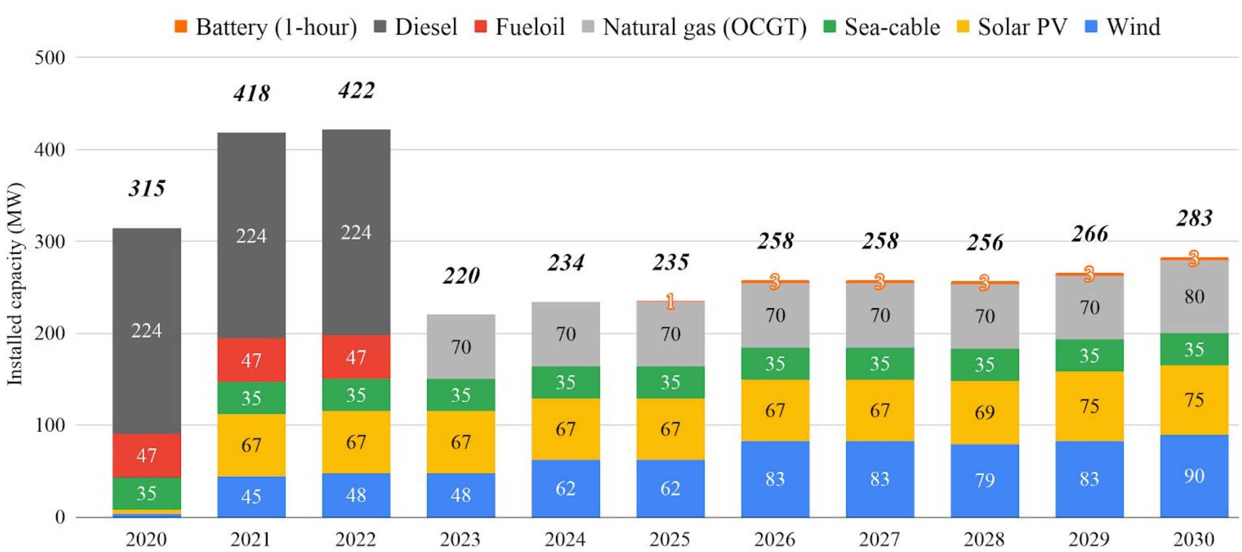

Figure 29 - Base case: evolution of installed capacity mix 2020-2030 (Elaboration: author)

The drastic reduction in the installed capacity of diesel and fuel-oil generators observed between 2022 and 2023 is the result of their deliberate retirement, modelled to take place by the end of 2022. Until then, they are both kept in operation since the associated investment has been amortized over many years of operation (more than two decades), making their dispatch the cost-optimum alternative relative to an early investment in new power generating assets[82].

Already in 2021, the first year modelled, significant investments in solar PV and (onshore) wind capacity – 67 MW and 45 MW respectively – are suggested by the model. From 2023 onwards, after the retirement of the diesel and fuel-oil generators, solar PV and wind[83] make up more than half of the total installed capacity in Menorca; a radical change in relation to the current generation mix (Figure 28).

Given the intermittency of solar and wind power, enough dispatchable capacity must be added to ensure the grid's reliability. In addition to the existing 35 MW from the sea-cable connecting Menorca to Mallorca, open-cycle natural gas turbines (OCGTs) represent the most efficient alternative. Based on their operational characteristics and the modelled fuel prices (Table 3), OCGTs can optimally complement solar PV and wind power plants to reliably meet demand, especially in regards to the (fast) ramp-up and -down capabilities needed to stabilize electrical networks with high penetration of variable renewable sources (i.e. solar PV and wind power).

Furthermore, it is interesting to note that despite their high efficiency (Table 3), combined-cycle gas turbines (CCGT) are not deployed at any point in time during the simulated years. This is explained by the large size of most commercial CCGT plants, which are usually built with capacities above 300-400 MW. The machinery used in these large-scale systems, such as heat recovery steam generators (HRSG), condensers and pumps, require sizable installations for commercial feasibility. For this reason, CCGT generators are modelled with a minimum unit size of 100 MW (Table 2), making the technology unviable for a power system as small as Menorca's[84]. Moreover, when compared to OCGTs, CCGTs have slower ramping capabilities

[82] All investment decisions made by the optimization algorithm aim to find the lowest cost solution by minimizing the combined NPV of all assets deployed throughout the ten years modelled.
[83] The reduction in wind power capacity in 2028 (Figure 29) is a consequence of the retirement of the 3.2 MW Milà power plant (Figure 12), modelled to go offline no later than 2028 after 25 years of operation (Table 2).
[84] This is confirmed by the fact that optimizations run with a minimum unit size of 75 MW for CCGT plants do include the technology as part of the solution.

and are therefore not as well suited to stabilize the rapid power output variations of intermittent sources such as solar PV and wind.

A relatively late and small deployment of Li-ion batteries with an energy-to-power ratio of one (1-hour batteries) can also be seen in Figure 29. The first megawatt is introduced in 2025 and by 2030 the total capacity amounts to 3 MW of power with 3 MWh of energy storage capacity. The batteries are mainly used to shift renewable energy to meet the evening peaks in demand, usually between 17:00 and 19:00. Due to their rapid response time (in the order of milliseconds), Li-ion batteries can also be used for frequency and voltage regulation of the electrical grid.

It is interesting to note that up until 2023, the techno-economic optimization leads to the addition of more solar photovoltaic than wind capacity (Figure 29). However, because more solar capacity means more electricity generation during the same hours (when the sun is shining), the marginal benefit of solar PV starts to decrease and wind becomes the preferred option for new generation from 2024 onwards. Throughout the 10-year period simulated, solar PV and (onshore) wind have proven to be the cheapest source of new generation, whereas natural gas is the preferable option when it comes to dispatchable sources.

4.1.2. Generation mix

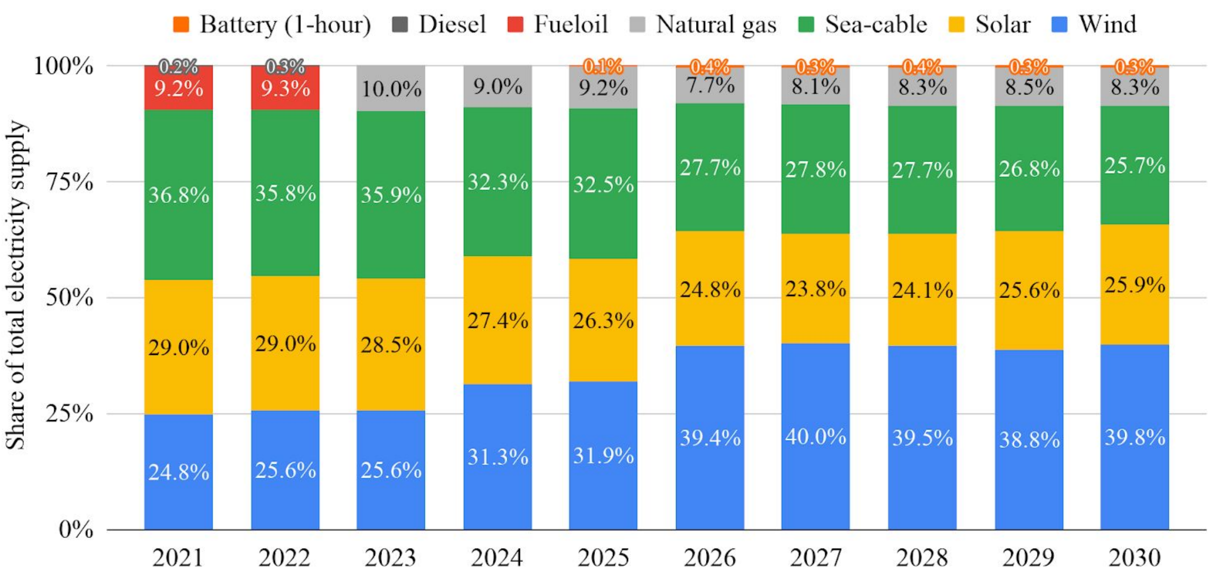

Figure 30 - Base case: evolution of electricity generation mix 2021-2030 (Elaboration: author)

Figure 30 shows the progression of the electricity supply mix during the 10-year time period modelled, from 2021 to 2030. As a result of the (idealized) immediate deployment of solar PV and wind power, already in 2021, more than 50% of the electricity demand of Menorca is met by renewables[85]. Despite not retired before 2023, the existing diesel and fuel-oil generators – from the GESA thermal plant – make up less than 10% of total supply in 2021 and 2022; with diesel representing less than 0.5% and fuel-oil about 9%[86].

The Mallorca-Menorca sea-cable represents the single largest source of electricity during the first five years of the simulation (2021-2025). However, as more renewable capacity is added to meet the annual growth in demand, the share of supply coming from the sea-cable slowly decreases while solar and wind take over as the main sources of electricity by 2030.

Despite the significant capacity of OCGT power plants shown in Figure 29 – with an initial deployment of 70 MW in 2023 (to replace the retired diesel and fuel-oil generators) and an additional 10 MW in 2030 – natural gas turbines are only occasionally used to supply electricity, mainly during specific times of high consumption, especially during the summer when demand reaches its peak (in the evening when not enough solar and wind resources are available). Such discrete use of the turbines leads to an overall small share of electricity coming from natural gas: 10% in 2023 and gradually decreasing to 8% in 2030 (Figure 30). As mentioned in the previous section, this seemingly excessive investment in natural gas capacity is not only necessary to ensure Menorca's power system can cope with the high seasonal variation in demand; it's also an essential source of spinning and contingency reserves to allow for a high penetration of intermittent renewables while ensuring the electrical grid's stability and reliability.

Although the optimized system has 3 MW of Li-ion batteries with a total of 3 MWh of energy storage capacity by the end of 2030 for the base case scenario, their total contribution to the annual supply of electricity is very limited, at less than 0.5% per year (Figure 30). Their role stays limited to an intraday time shift of renewable generation to match demand.

4.1.3. Generation profile

Another important aspect to be analyzed is how each power generation technology is dispatched throughout the days and months to meet Menorca's hourly electricity demand from 2021 to 2030. Given that the model includes a total of more than ten thousand hours of simulation for

[85] Note that *Switch 2.0* makes investment decisions at the beginning of every period (i.e. year), whereby new generation assets are instantaneously deployed and can be dispatched at the very first hour of that period (construction and commissioning times are disregarded by the model).
[86] Fuel-oil is modelled with a significantly lower price than diesel (Table 3), thus it is deployed much more often.

each scenario, the generation profile for weekly time intervals, which can be graphically represented in a clear and comprehensible way, is plotted for the years 2021, 2025 and 2030 (Figure 31).

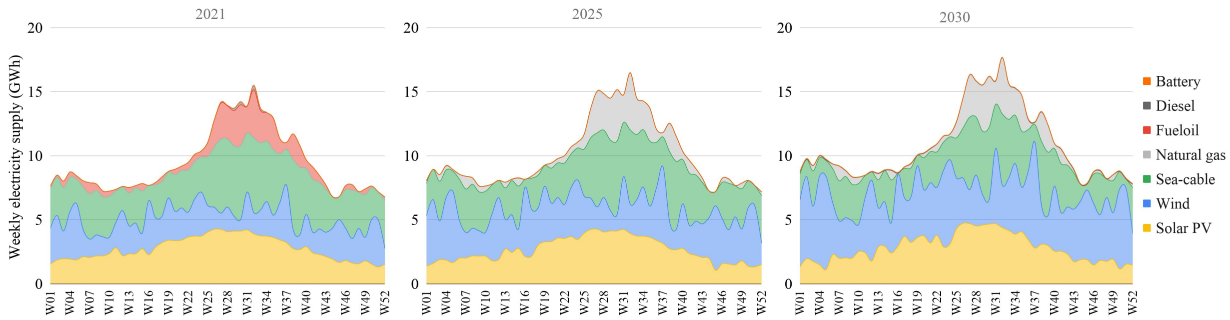

Figure 31 - Weekly electricity generation profile in 2021, 2025 and 2030 (Elaboration: author)

While the existing fuel-oil generators (from the GESA thermal plant) can be seen as a significant source of electricity during the summer of 2021, after being retired at the end of 2022, their contribution is mostly replaced by (OCGT) natural gas generators.

Although fuel-based power generation seems to be mainly dispatched to meet the increased consumption observed during the summer weeks, their existence is crucial for the electrical network's stability. As dispatchable synchronous machines, natural gas turbines can provide ancillary services and be used as spinning reserves, allowing system operators to better regulate the grid's frequency and voltage. Such characteristics are especially relevant for systems with high penetration of variable renewable sources, which lack inertia and flexibility.

Already in 2021, combined solar PV and wind power generation supply more than half of the electricity consumed in Menorca for most of the year. The variations in both solar irradiation levels and wind speeds (as well as their randomization) can be observed in the generation profiles in Figure 31. While solar shows a clear seasonal pattern, wind generation is seen as much more stochastic, varying significantly throughout the weeks.

The sea-cable interconnection indirectly linking Menorca to Spain's peninsular electrical system (Figure 13) offers a lot of flexibility to Menorca's power system, playing an important role in the continuous balancing of supply and demand[87]. Interestingly, based on the modelled prices (Table 3), the sea-cable represents a more economical generation option when compared to

[87] Although the optimization does not include the benefits of exporting power through the sea-cable, it must be noted that it is a possibility in situations of excess generation due to favorable solar and wind conditions.

natural gas, being dispatched more frequently throughout the year and consequently providing a larger share of the total annual electricity supply (Figure 30). As a dispatchable source, the submarine interconnection also assists in the integration of solar PV and wind power to Menorca's grid, in addition to being capable of providing several important ancillary services.

To demonstrate how the different technologies operate together to continuously meet Menorca's electricity demand, the hourly generation for the day with the highest consumption[88] in 2021, 2025 and 2030 is shown in Figure 32. The increased time granularity of the charts allows for a clear view of the lithium-ion batteries being dispatched to meet the evening peak, which takes place around 18:00-19:00.

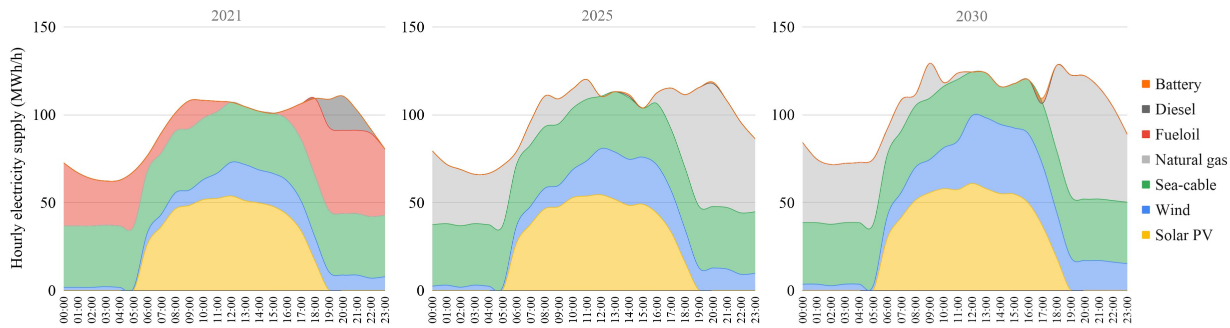

Figure 32 - Generation profile for the day with highest demand in 2021, 2025 and 2030 (Elaboration: author)

Because solar PV is modelled in a fixed-axis configuration (Table 4), it presents a generation highly correlated to the sun's path in the sky, gradually increasing as the sun rises, peaking around midday and steadily decreasing in the afternoon until it reaches zero as the sun sets. Small fluctuations can be observed in the solar generation curves (Figure 32). These are simply due to the randomization of hourly irradiation levels aimed at simulating variations caused by cloud coverage and other changes in weather conditions. As an intermittent energy source, wind power also shows some variability throughout the day, with generation reaching the highest levels in the afternoon for the three specific summer days shown in Figure 32.

Finally, the sea-cable and fossil-based generators are used to supply the remaining power needed to match consumption. As dispatchable sources, their output is continuously adjusted to ensure a perfect balance between supply and demand, at all times. Once again, their flexibility as dispatchable sources is seen playing a crucial role for the integration of intermittent renewables.

[88] The day with the highest simulated consumption happens in week 32 (1st half of August) for all three years: 2021, 2025 and 2030. These are also the days when instantaneous power demand peaks for the respective years.

4.1.4. Carbon emissions

As nations and communities around the world struggle to transition to low-carbon energy solutions in an attempt to mitigate climate change, it is important to assess the carbon footprint associated with a cost-optimized power system. Menorca's grid is heavily reliant on a single power plant – GESA – made up of diesel and fuel-oil generators (Figure 28). After being electrically disconnected from Mallorca in 2017, more than 95% of Menorca's electricity supply came from the GESA thermal plant, resulting in a carbon footprint about four times higher than Spain's national levels (Figure 14–left). With the newly installed sea-cable coming online in the summer of 2020, electricity-related emissions are likely to decrease going forward; though the extent of this reduction is highly dependent on the energy source of the power imported through the submarine interconnection. If Spain continues to increase the penetration of renewables to meet national and European climate targets, the sea-cable will allow for ever cleaner electricity to be imported to Menorca[89].

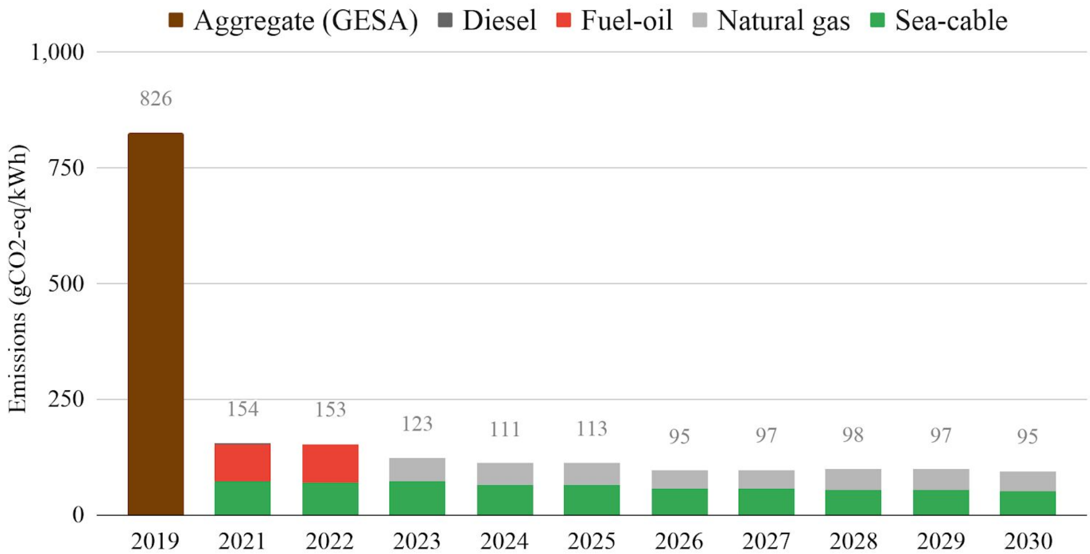

Figure 33 - Base case: evolution of Menorca's electricity-related carbon emissions[90] (Elaboration: author)

Menorca's 2019 electricity-related emissions together with those of the optimization results for the base case scenario are shown in Figure 33. The introduction of about 100 MW of combined solar PV and wind power capacity in 2021 (Figure 29) prompts an 81% drop in emissions

[89] The carbon footprint of the power provided by the sea-cable (202 gCO2-eq/kWh) is modelled based on Spain's 2019 electricity-related emissions and a 95% transmission efficiency. It's kept constant for the entire study period.
[90] Note that 2020 is omitted as it is the current (unfinished) year. Emissions for 2019 are presented as the total aggregate from the GESA thermal power plant (a consolidation of diesel and fuel-oil generation), since discrete data is not available to the author.

(relative to 2019), from 826 to 154 grams of CO_2-equivalent per kilowatt-hour. From 2021 to 2026, as more solar PV and wind capacity are deployed, emissions continue to decrease steadily, stabilizing around 95 gCO_2-eq/kWh by 2030, a reduction of almost 90% from 2019 levels.

This significant reduction in the carbon emissions of Menorca's power system (Figure 33) is the result of a purely cost-driven optimization analysis in which no carbon price or emissions trading scheme is introduced, and market risks associated with fossil fuel price fluctuations are completely disregarded. Hence, the results highlight how the continuous decrease in the cost of renewable energy (Figure 21–left) is allowing technologies such as solar PV and wind power to compete with fossil-based sources for electricity generation, without any type of incentive or subsidy scheme.

4.2. Scenario 1 - Carbon pricing

Against the backdrop of the results observed for base case scenario (Section 4.1.), it is now possible to evaluate the effect of specific parameters on the optimization results. The first alternative scenario assesses the sensitivity of the model to different levels of carbon price. As a byproduct of fossil-based power plants, carbon emissions represent an externality with many adverse effects, especially in terms of the global warming potential of GHGs such as methane and carbon dioxide.

Several governments and authorities have implemented mechanisms to price carbon in an attempt to preserve the dynamism of free markets while ensuring that the emissions externality is appropriately priced in. One interesting and relevant example of a carbon pricing scheme is the European Union's *Emissions Trading System* (ETS), which works based on a *"cap and trade"* principle [109]:

- A cap is set on the total amount of emissions allowed for certain greenhouse gases that can be emitted by installations covered by the scheme;
- The cap is reduced over time so that total emissions fall;
- Within the cap, companies receive or buy emission allowances, which they can trade with one another as needed (the cap limit on the total number of allowances available ensures that they have a value);

- After each year, participants must surrender enough allowances to cover all its emissions, otherwise fines are imposed. If a company reduces its emissions, it can keep the spare allowances to cover its future needs or else sell them to another company that is short of allowances;

- Trading brings flexibility that ensures emissions are cut where it costs least to do so. A robust carbon price also promotes investments in clean, low-carbon technologies;

In order to better understand the effect of pricing carbon emissions on the techno-economic optimization of Menorca's power system, five different pricing levels are simulated: €0, €20, €50, €80 and €100 per tonne of carbon[91]. The results are presented and compared in the following sections.

4.2.1. Installed capacity

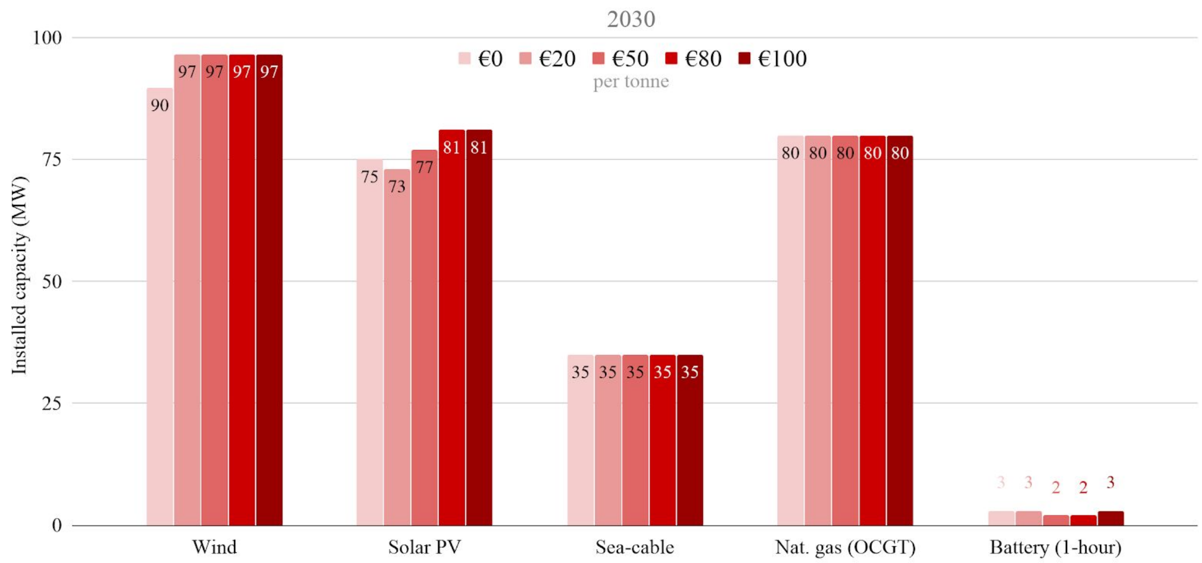

Figure 34 - Total installed capacity in 2030 for different carbon price levels (Elaboration: author)

Despite the wide price range considered, from €0 to €100 per tonne of carbon emitted, the installed capacity of each power generating technology remains relatively similar by the end of 2030 (Figure 34). For all carbon price levels modelled, no change in the total installed capacity for the sea-cable and natural gas (OCGT) generators is proposed by the cost optimization. At €20 per tonne, the carbon price is enough to cause the deployment of 7 MW of additional wind capacity (two of the 3.45 MW turbines modelled). This extra wind power capacity, together with the 3 MW of batteries, is enough to displace 2 MW of solar PV, which are no longer needed.

Figure 34 also shows that as the carbon price increases, the system's total solar PV capacity in 2030 grows; mainly because at 97 MW wind has reached the maximum capacity limit imposed

[91] Note that a scenario with a carbon price of €0 per tonne is equivalent to the base case scenario.

on the model[92]. In contrast, the sea-cable capacity stays constant at the currently installed 35 MW in all cases. Similarly, the natural gas (OCGT) cumulative capacity added by 2030 remains the same at 80 MW, whereas, despite their lower carbon footprint (Figure 27), CCGT plants are not part of a cost-optimum power system for any of the carbon prices simulated.

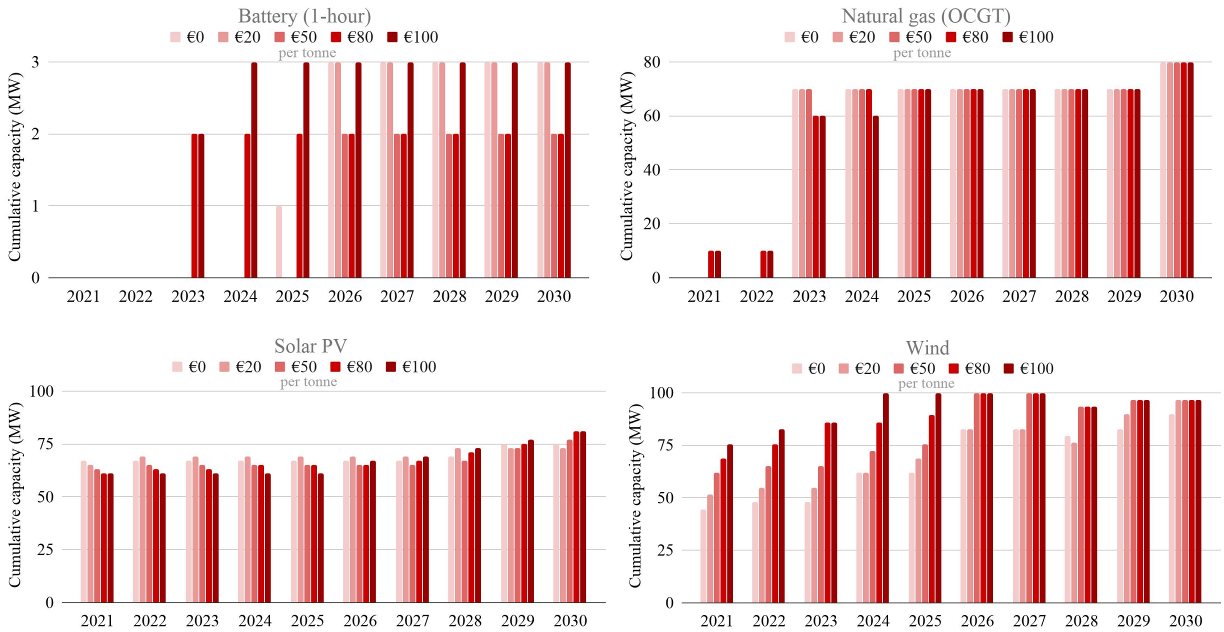

Figure 35 - Cumulative capacity of different power technologies for each carbon price level (Elaboration: author)

In addition to the variations in the total installed capacity of the different power generating technologies for each of the carbon prices analysed, another important consideration is their effects on the deployment timing of new generators. Higher carbon prices induce an earlier switch to cleaner technologies, with more batteries and wind power capacity being built earlier as the price of emitting increases. The more expensive the carbon price is, the higher the total renewable capacity becomes. Though not included in Figure 35, the sea-cable capacity stays flat at 35 MW from 2021 to 2030 for all carbon prices simulated.

In the case of natural gas, 10 MW of OCGT capacity is deployed as early as 2021 for carbon prices of €80 and €100 per tonne; even though the existing 271 MW fleet of diesel and fuel-oil generators is modelled to only retire at the end of 2022. As a less carbon intensive energy source (Figure 27), an earlier investment in OCGT plants is justified at these higher carbon price levels.

[92] Because the modelled wind turbine has a rated power of 3.45 MW, the addition of another one would cause the total installed capacity to surpass the 100 MW limit imposed on the model (Table 2). The maximum number of wind turbines possible within the 100 MW maximum capacity constraint is 28 (96.6 MW).

4.2.2. Generation mix

To fully understand the impact of pricing carbon emissions, it is essential to analyse its effect on the dispatch of each power generation technology throughout the simulated years. Figure 36 shows the impact of each carbon price level on the electricity supply mix for the years 2021, 2025 and 2030.

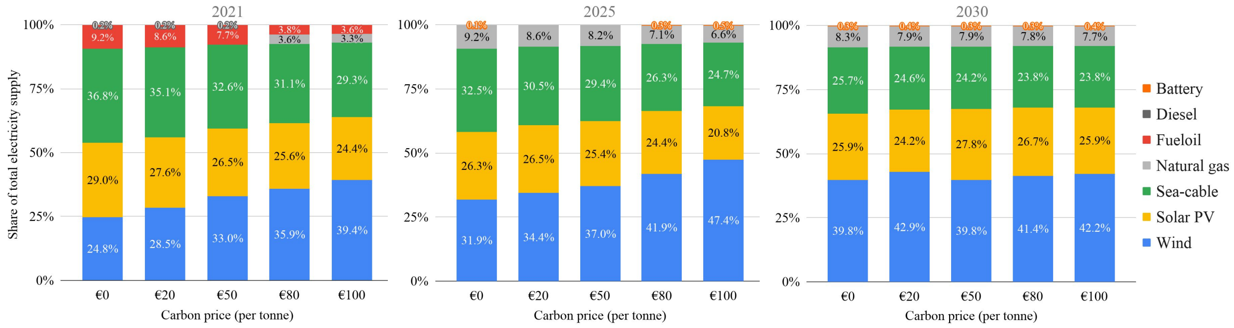

Figure 36 - Generation mix at different carbon pricing levels in 2021, 2025 and 2030 (Elaboration: author)

The correlation between the price paid to emit and the amount of renewable energy generation is clear for the years 2021 and 2025; whereas in 2030 it becomes much less pronounced (Figure 36). This implies that higher levels of carbon pricing are more impactful to the electricity supply mix in the earlier years, causing investments in clean technologies to happen sooner than they otherwise would for a cost-optimum system. Nevertheless, the effect of higher carbon prices is very limited for 2030, a year in which renewable generation grows by a mere 2% when going from €0 to €100 per tonne.

Interestingly, despite causing a reduction in overall emissions for the 10-year period simulated (Section 4.2.3.), increased carbon prices levels have a limited effect on the electricity supply mix of a cost-optimum power system for Menorca in 2030. This shows, once again, how clean energy technologies such as solar PV and wind power are becoming cheap enough to the point where they can outcompete fossil-based generators, even when emissions are not priced at all.

4.2.3. Carbon emissions

Given that the main goal of carbon pricing schemes is to induce markets to efficiently allocate resources while ensuring that the emission externality is accounted for, it is paramount to analyse how the carbon footprint of a cost-optimized power system is affected by different levels of carbon pricing for the 10-year study period (2021-2030).

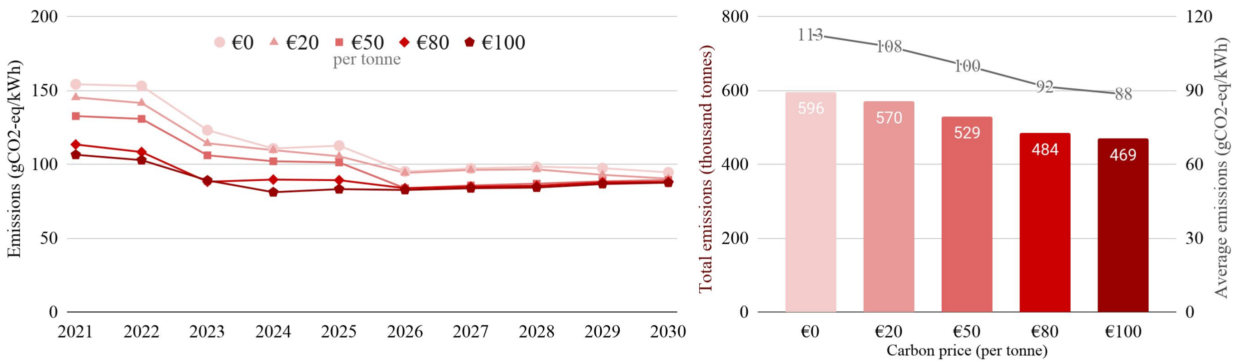

Figure 37 - Carbon footprint evolution (left). Total and average carbon emissions from 2021 to 2030 (right) (Elaboration: author)

The previously discussed effect of higher carbon price levels on the timing of the deployment of renewable energy technologies can also be seen in the progression of electricity-related emissions from 2021 to 2030. A higher price paid to emit pushes the cost-optimization to source more power from clean generators sooner, causing a reduction in emissions that is most noticeable in the earlier years, from 2021 to 2025 (Figure 37–left). After 2025, the difference becomes less significant, mostly because the cost reduction curve experienced by solar PV and wind power (Table 3) makes them cheap enough for their implementation to be economical even at lower carbon prices.

The overall evolution of the power system's generation mix from 2021 to 2030 results in fairly distinct levels of total and average electricity-related emissions. Total carbon emissions during the 10-year study period drop by about 21% when carbon prices are increased from €0 to €100 per tonne, with the grid's average carbon footprint being reduced from 113 to 88 grams of CO_2 per kilowatt-hour (Figure 37–right).

4.3. Scenario 2 - Renewable portfolio standards

Another interesting externality that shall be explored by this study is the introduction of a commonly discussed government policy geared towards mitigating climate change: renewable portfolio standards (RPS), also referred to as renewable mandates. Despite this study's focus on a market oriented approach for the techno-economic optimization of Menorca's power system, the implementation of a RPS scenario is deemed worthy of a dedicated analysis due to the 85% renewable target proposed by the *Consell Insular de Menorca* (the island's local government) in its *Menorca Roadmap 2030* energy transition plan.

The RPS levels simulated and analyzed are: 75%, 85% and 95% by 2030[93]. In order for the algorithm to find a solution that satisfies the RPS constraint added to the model, the maximum capacity limitation previously imposed for both solar PV and wind power (300 and 100 MW respectively) must be relaxed. Hence, the RPS scenario is simulated with no upper bound on the capacity of solar PV or wind power that can be deployed.

4.3.1. Installed capacity

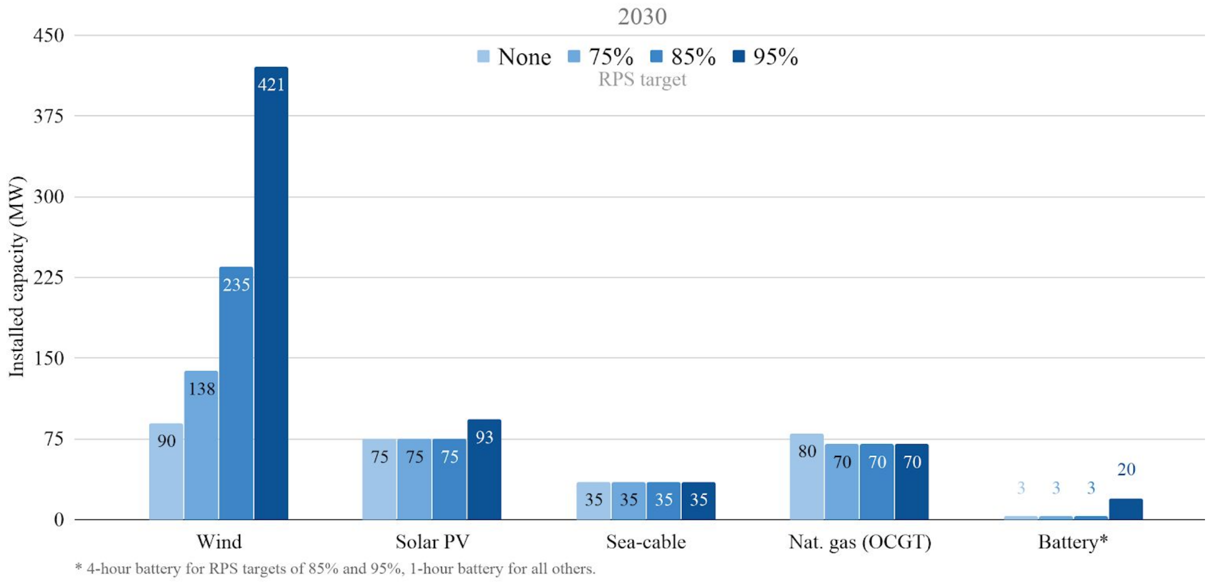

Figure 38 - Total installed capacity in 2030 for different RPS target levels (Elaboration: author)

As renewable sources, solar PV and wind power are directly impacted by an RPS mandate. Despite having a higher cost per megawatt (Table 3), wind turbines are seen as the preferred generating technology to meet higher RPS targets, mainly because of a higher annual capacity factor when compared to solar PV: 34% and 26% respectively. A cost-optimum power system capable of meeting an RPS target of 95% by 2030 requires more than 500 MW of combined renewable capacity, in addition to 20 MW of lithium-ion batteries with 80 MWh of energy storage capacity to shift excess solar PV and wind energy to match demand (Figure 38).

Figure 38 shows how it becomes increasingly challenging to increase the penetration of renewables beyond the 90% level. The cannibalization effect experienced by solar PV and wind power requires the system to be significantly oversized and large amounts of energy storage capacity (i.e. batteries) to be deployed.

[93] The accounting of renewable energy is done as a percentage of total generation (not demand) in order to include system losses and accurately account for storage projects (i.e. batteries), which can be charged by both fossil-based and carbon-free generators. (*Switch*'s original RPS calculation algorithm has been adapted accordingly).

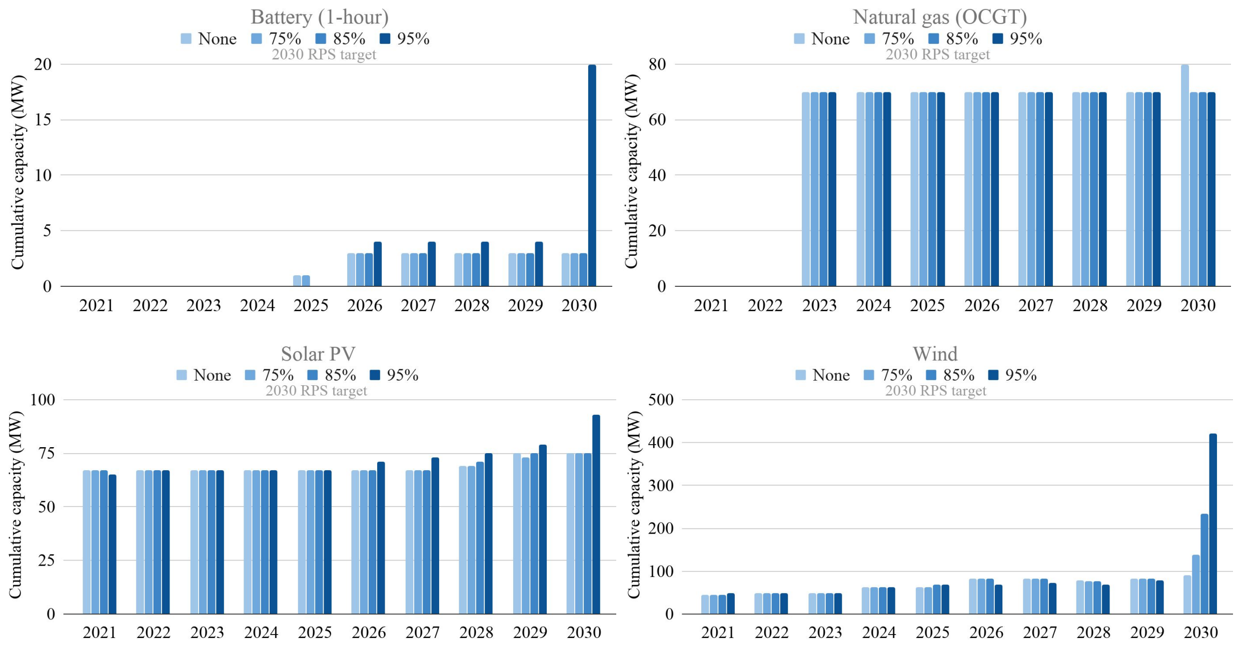

Figure 39 - Cumulative capacity of different power technologies for each RPS target (Elaboration: author)

While total natural gas capacity is 70 MW for all (non-zero) RPS levels, it increases to 80 MW in the absence of a renewable mandate (Figure 39). Such limited variation can be explained by its role as controllable and dispatchable capacity, improving the electrical grid's flexibility and providing ancillary services. In addition, gas turbines may also be used as backup generation in case of contingencies, such as failure of other power generation assets or several continuous days of unfavorable weather conditions that may impact solar PV and wind power output.

Both solar PV and wind power capacities grow with higher RPS targets, with most of the additional renewable capacity being allocated to additional wind turbines (Figure 39), which have a higher load factor (i.e. capacity factor) than solar PV, representing the most cost-efficient alternative.

Although not an intrinsically renewable energy source, batteries are an essential piece of the RPS puzzle, allowing energy from solar PV and wind power plants to be stored and supplied when needed. At a 95% RPS target, the amount of battery capacity needed grows significantly, since the system can only source 5% of total electricity supply from natural gas or the sea-cable.

Since the electricity imported through the sea-cable is generated by a variable mix of technologies, it is not modelled as an RPS eligible source. Consequently, its total capacity remains constant at the currently installed 35 MW for all RPS levels modelled.

4.3.2. Generation mix

While the installed capacity provides a good picture of the types of power technologies to be invested in for a cost-optimum system, the generation mix shows the participation of each one in supplying electricity to Menorca.

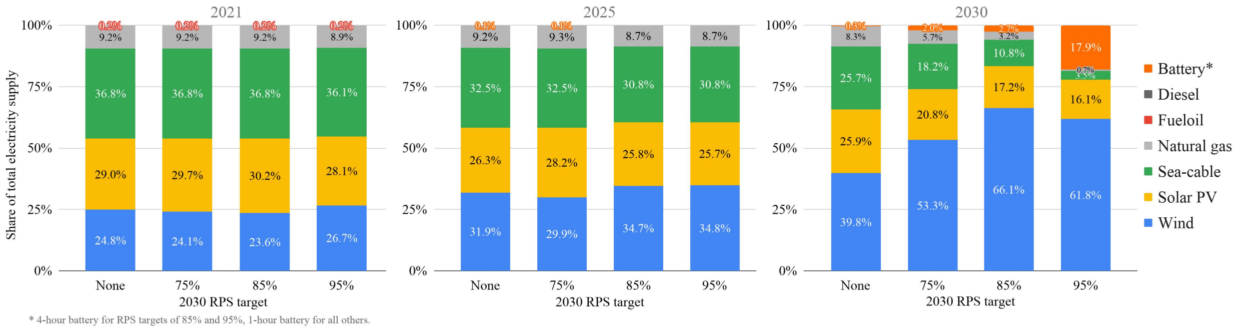

Figure 40 - Generation mix at different RPS levels in 2021, 2025 and 2030[94] (Elaboration: author)

Figure 40 presents the share of electricity supplied by the different generation technologies deployed. Since the renewable portfolio standards are set to be met by 2030 – the last year simulated – 2021 experiences little change for each of the four cases analysed. On the other hand, as the deadline year for compliance with the established renewable mandate levels approaches, a notable correlation between RPS targets and the share of supply coming from renewable sources: solar PV and wind.

By 2030, batteries become an important part of a cost-optimized system, allowing for cheap but intermittent electricity from solar PV and wind power plants to be stored and shifted in time to meet demand when the sun is not shining or the wind is not blowing.

The 70 MW of natural gas (OCGT) installed capacity for RPS levels of 75%, 85% and 95% (Figure 38) is seldom dispatched in 2030, mostly serving as reserve to meet peak demand, for example during summer days in which weather conditions are unfavorable for solar and wind power generation. Nevertheless, as synchronous generators with rapid ramp-up and -down capabilities, open cycle gas turbines can also provide essential ancillary services to the system operator, such as voltage and frequency regulation. These services are paramount to ensure a stable and reliable electrical grid, especially one with a high share of solar PV and wind power.

[94] Note that the RPS calculation is done excluding batteries, which as an energy storage technology, is not intrinsically renewable (it can also be charged with fossil-based electricity). In order to check that RPS targets are indeed met by 2030, the calculation must be done on the basis of generation only, excluding the batteries' share of supply from the denominator.

4.3.3. Carbon emissions

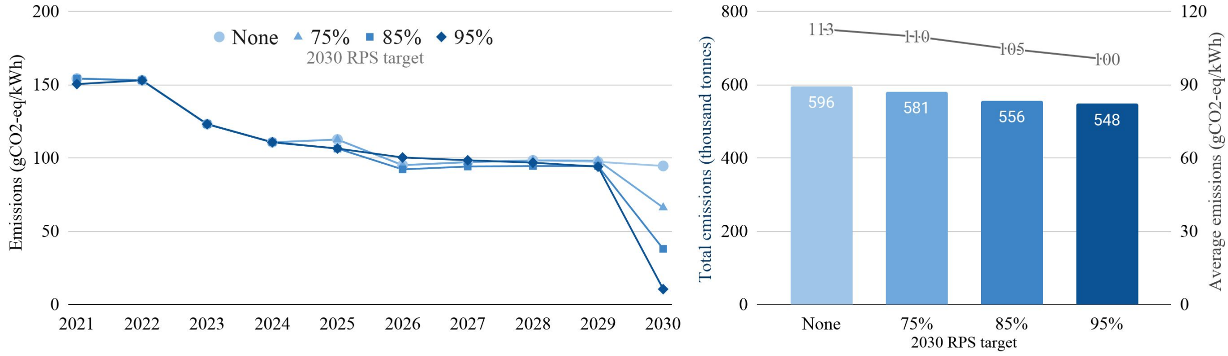

Figure 41 - Carbon footprint evolution (left). Total and average carbon emissions from 2021 to 2030 (right) (Elaboration: author)

Because the RPS mandates are modelled to be met by 2030, from 2025 to 2029 the share of renewable generation is similar for all levels simulated, fluctuating around 63%. This can be observed by the small difference in the level of carbon emissions. However, in order to meet each respective RPS target, more renewable capacity is dispatched in 2030, causing electricity-related emissions to drop significantly that year (Figure 41–left).

For a RPS target of 85% the grid's carbon footprint drops below 40 gCO_2-eq/kWh, whereas for a 95% target it reaches the extremely low level of 10 gCO_2-eq/kWh. For context, in 2019, the Spanish electrical grid had emissions of 192 gCO_2-eq/kWh (Figure 14); while Iceland, a country with one of the cleanest grids in the world, emitted about 27 gCO_2-eq/kWh that same year [110].

Total and average carbon emissions for the 10-year study period decrease gradually as the RPS target is raised, dropping by more than 10% in the case of a 95% RPS mandate relative to the base case, which imposes no mandate for renewables (Figure 41–right).

4.4. Scenario 3 - Natural gas price hedging

Finally, the last scenario aims to assess how the risks associated with market fluctuations in the price of natural gas might impact the results of the techno-economic optimization. Although capital markets offer several different instruments to mitigate such exposure (e.g. swaps, options, futures, etc), the price hedging mechanism considered for this scenario is abstracted as a percentage increase in total annual natural gas expenditures. Therefore, the introduction of a fuel price hedging mechanism – in this case for natural gas – internalizes the risks associated with market variations by affecting the operational (variable) cost of fuel-based generators.

Four different annual hedging costs are implemented: 1%, 2%, 5% and 10%; in addition to the base case scenario, which is modelled with constant natural gas prices (i.e. 0% hedging cost). The average Spanish natural gas price of the last five years (including levies and taxes) used in the base case (€10.46/MMBtu [111]) is taken as the baseline for the first year, 2021. Thereafter, natural gas prices increase and compound yearly by the respective hedging cost considered for each case simulated (0%, 1%, 2%, 5% or 10%) until 2030.

4.4.1. Installed capacity

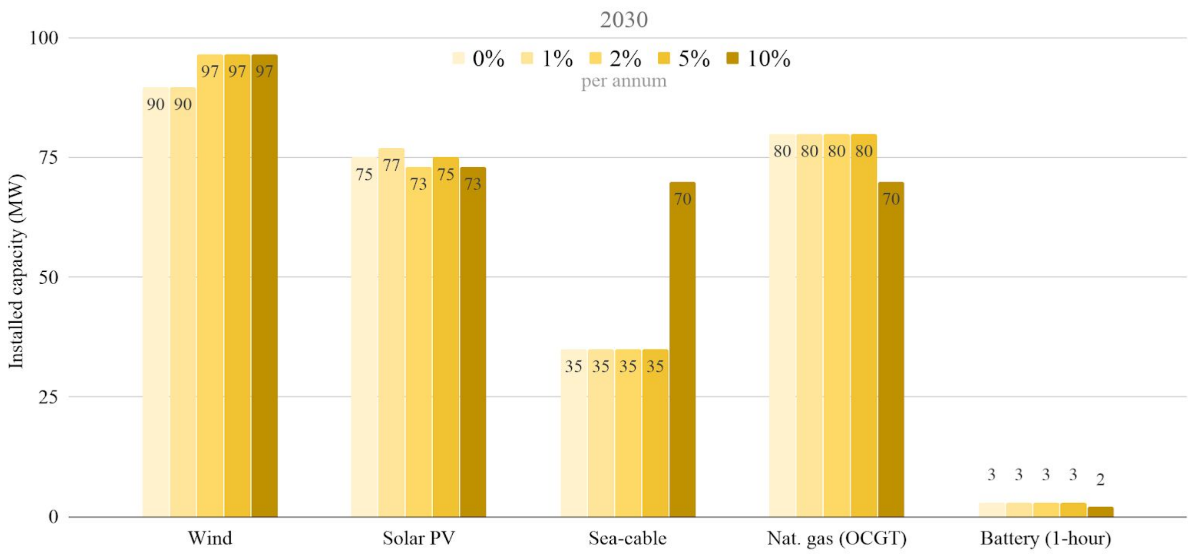

Figure 42 - Total installed capacity in 2030 for different natural gas hedging costs (Elaboration: author)

By 2030, natural gas (OCGT) plants have the same cumulative capacity of 80 MW for hedging costs of up to 5% a year. At the 10% level, OCGT's total installed capacity is lower at 70 MW, as 10 MW are replaced by the deployment of a second 35 MW sea-cable interconnection, the most economical alternative (Figure 42).

Similar to what is observed for the carbon pricing scenario (Section 4.2.), combined solar PV and wind power capacity remains relatively stable, highlighting (once again) the eventual degradation of the marginal benefit of intermittent renewables, particularly noticeable when not coupled with storage technologies. Batteries, which could be a well-suited technology to mitigate this effect, are relatively expensive and thus have limited economic feasibility. Their total installed capacity is 3 MW (3 MWh of energy storage) for hedging costs of up to 5% per year; whereas at a 10% level, the second sea-cable displaces 1 MW of battery capacity, bringing it to a total of 2 MW and 2 MWh of storage.

Figure 43 - Cumulative capacity for different natural gas hedging costs (Elaboration: author)

Figure 43 shows the yearly progression of the installed capacity for Li-ion batteries, natural gas (OCGTs), solar PV and wind power for the entirety of the 10-year study period[95]. As electricity demand grows and the premium paid annually to hedge natural gas prices is compounded, dispatching gas turbines becomes increasingly more expensive. As a consequence, the cost-optimization algorithm opts to expand the system's renewable capacity by building more solar PV and especially wind power plants in the years leading up to 2030.

Interestingly, the base case (i.e. 0% hedging cost) sees the earliest deployment of a battery storage system, with a 1 MW – 1 MWh battery in 2025. At a 10% hedging cost, the highest level simulated, 2 MW of battery capacity (with 2 MWh of storage) is built in 2026, with no additional capacity added later. For all other cases, the total battery capacity is 3 MW (with 3 MWh of energy storage), deployed in 2026 and staying constant thereafter.

It may seem counterintuitive that the case with the highest natural gas costs is the one with the lowest final storage capacity; after all, storage can be an effective way to increase renewable energy penetration and thereby reduce fuel dependence. However, the objective function of the optimization algorithm is to minimize the net present value (NPV) of the entire power system. As such, the algorithmic simulations allow the model to perform calculations with the benefit of

[95] The sea-cable is omitted from Figure 43 since it has a constant capacity of 35 MW for all hedging cost levels from 2021 to 2029, with an additional 35 MW of capacity added in 2030 for the 10% case alone (Figure 42).

a hindsight perspective, in which investment decisions made at the beginning of year *X* influence and are influenced by the decisions made at years *X+1, X+2,* all the way up to 2030. In other words, investment decisions do not follow a sequential and linear time progression, being actually codependent and made in coordination with the ultimate goal of identifying the unique combination of installed capacities that can successfully meet the simulated electricity demand from 2021 to 2030 and has the lowest NPV of all permutations possible.

4.4.2. Generation mix

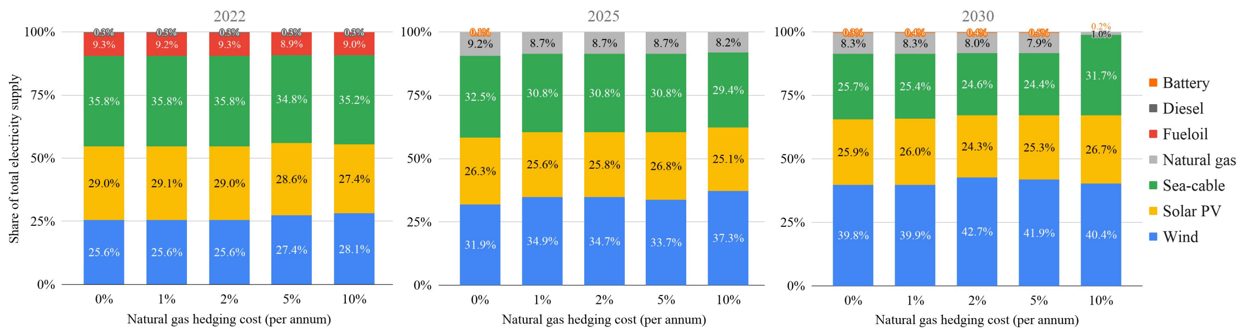

Figure 44 - Generation mix for different natural gas hedging costs in 2022, 2025 and 2030 (Elaboration: author)

Because 2021 is the baseline year, it is modelled with the same natural gas prices across all cases. Hence 2022 is the first year depicted in Figure 44, and shows very small variations in the share of electricity supply provided by each power generating technology. After compounding for four years, natural gas hedging costs start to have a more pronounced impact in 2025, most notably in the growth of the share of electricity coming from wind – a carbon-free source[96].

By 2030, a 10% price premium to hedge fuel prices has a drastic effect on Menorca's power supply mix, with the installation of a second sea-cable displacing 87.5% of the natural gas generation (Figure 44). Batteries continue to play a very marginal role, contributing less than 1% of the total supply across all cases, serving mainly to shift renewable energy generation to help meet the evening peaks in demand, particularly during the summer months.

4.4.3. Carbon emissions

While the added cost of hedging natural gas prices eliminates most of the risks associated with market fluctuations, it also imposes a premium on the economical feasibility of burning gas for electricity generation, thus affecting the competitiveness of gas turbines relative to the other

[96] The manufacturing of wind turbines and construction of wind power plants do involve significant amounts of fossil fuels and carbon emissions. In this context *carbon-free* refers strictly to the power generation stage.

generators modelled. Since natural gas represents the most carbon intensive alternative of all the power technologies considered for new generation[97] (Figure 27), hedging fuel costs have a direct correlation with the carbon footprint of a cost-optimum system.

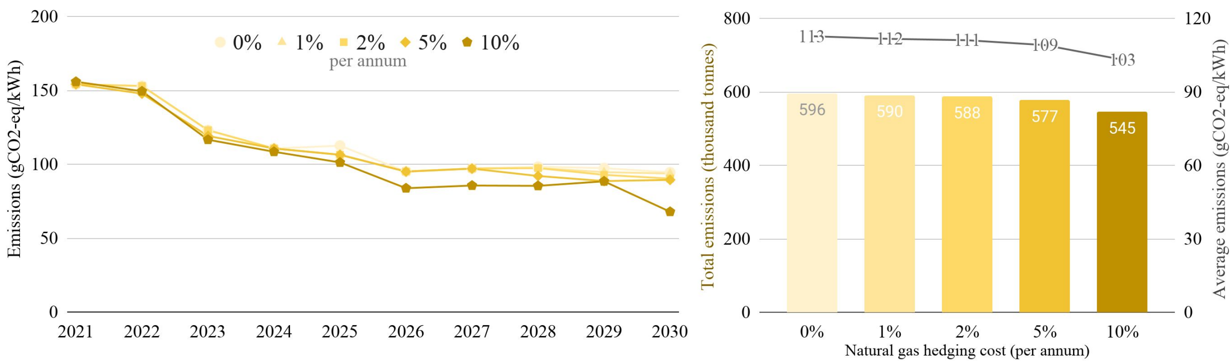

Figure 45 - Carbon footprint evolution (left). Total and average carbon emissions from 2021 to 2030 (right) (Elaboration: author)

From 2021 to 2030, electricity-related emissions fall for all hedging costs considered. By 2030, the grid's carbon-footprint drops to around 92 gCO_2-eq/kWh for all cases simulated, with the exception of a 10% annual hedging cost, which results in emission levels of 68 gCO_2-eq/kWh in 2030 (Figure 45–left).

In terms of the overall cumulative emissions for the 10-year period, higher natural gas hedging costs do imply a reduction in the total amount of carbon emitted and, consequently, in the average carbon footprint. Nonetheless, though a 10% annual premium to hedge natural gas compounded over a 10-year period causes prices to more than double by 2030, total carbon emissions from 2021 to 2030 fall by less than 10% (Figure 45–right). This relatively limited impact on the carbon footprint highlights the indispensability of dispatchable generators, represented in the model by non carbon-free sources: the sea-cable and gas turbines.

For a system in which intermittent technologies become the main sources of electricity, the flexibility offered by other complementing generating assets plays a crucial role ensuring a continuous supply of power to the network, regardless of what weather conditions might be. In this regard, batteries are only economical for very short term needs, in the order of a few hours (intraday). By contrast, the sea-cable and OCGTs are more economical when it comes to large-scale supply of power for many hours to days, thus playing a crucial role in ensuring the system's reliability in a cost efficient way.

[97] This excludes diesel and fuel-oil, which are not considered for new generation projects in the model.

4.5. Scenario comparison

With the results of the cost optimization for the base case and the three alternative scenarios modelled presented, comparisons and parallels can now be drawn, including an interpretation of financial aspects.

4.5.1. Installed capacity

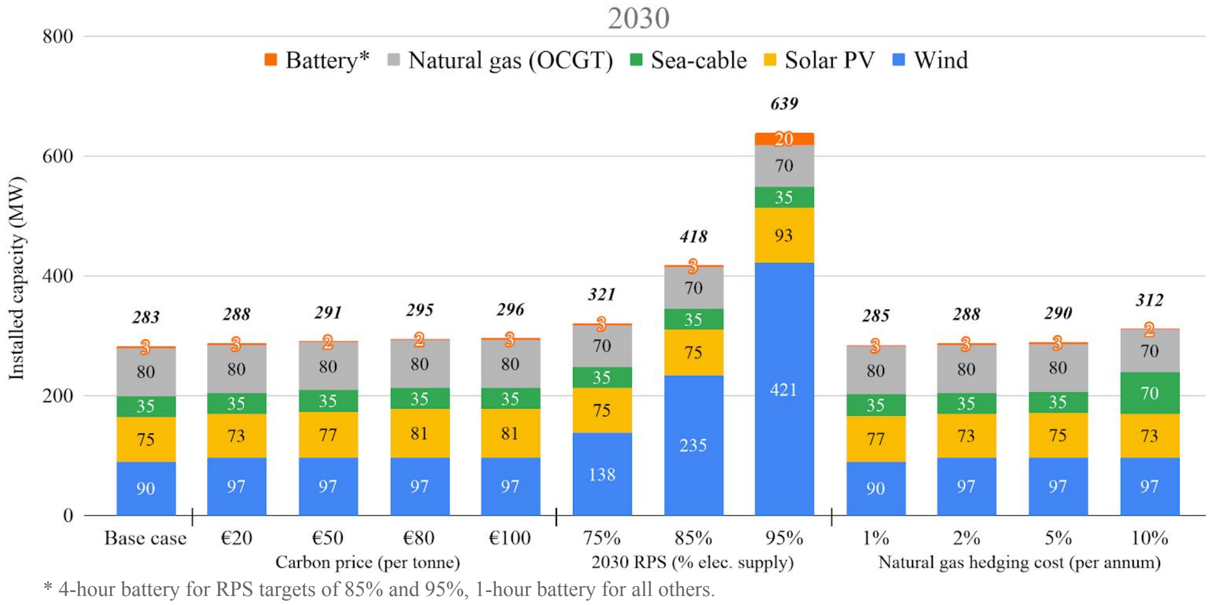

Figure 46 - Comparison of the cumulative installed capacity in 2030 for all scenarios (Elaboration: author)

With the exception of the RPS scenarios, a cost optimum power system for Menorca has a total installed capacity of about 300 MW by 2030, of which more than half consists of solar PV and wind power plants[98] (Figure 46).

The only fuel-based power generation technology to be built in any of the scenarios analysed was open-cycle gas turbines (OCGT). Despite being modelled, combined-cycle gas turbines (with and without carbon capture capabilities) are not deployed despite having higher (electrical) efficiency and a lower carbon footprint. This is explained by the minimum capacity of 100 MW imposed on the model for CCGT plants, which simply makes the investment unfeasible given that 80 MW of dispatchable fuel-based capacity in combination with the existing 35 MW sea-cable interconnection are enough to cope with a high penetration of intermittent renewables, solar PV and wind power, which represent the cheapest sources of new generation.

[98] Note that the capacity limit of 300 MW for solar PV and 100 MW for wind are removed for the RPS scenarios.

For all but one of the cases simulated, the sea-cable capacity remained unchanged at 35 MW. For a 10% annual hedging cost, which causes gas prices to more than double by 2030, a second 35 MW sea-cable is deployed, displacing 10 MW of natural gas (OCGT) capacity (Figure 46).

Although batteries are part of a cost optimum power system for Menorca in the next ten years, their participation is limited to 2-3 MW with one hour of energy storage capacity being enough for all but the 85% and 95% RPS scenarios. The imposition of a renewable mandate requiring 95% of the electricity supply to come from renewable sources has a significant impact on the generation fleet deployed, with a system that is much bigger in size and needs a lot more storage to be able to time-shift excess electricity from intermittent renewables (Figure 46).

4.5.2. Generation mix

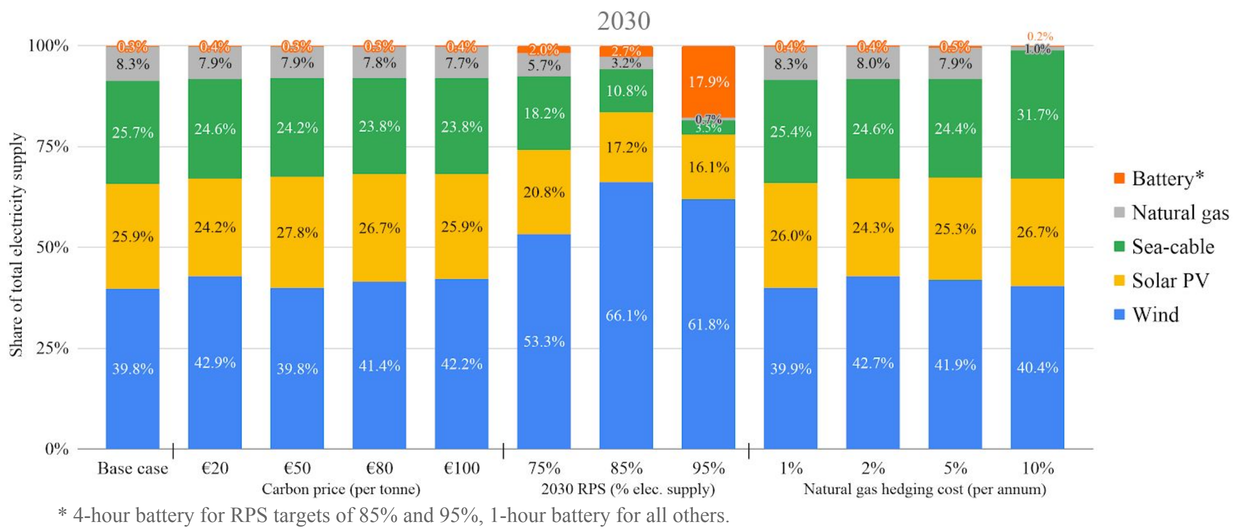

Figure 47 - Comparison of electricity generation mix in 2030 for all scenarios (Elaboration: author)

A comparison of the 2030 electricity generation mix for all scenarios (Figure 47) shows surprisingly little variation for all but the RPS scenarios. Renewables provide about two thirds of the electricity supply, while the sea-cable makes up a quarter of the total, leaving less than 10% to be supplied by (OCGT) natural gas plants and batteries. These results highlight the competitiveness of both solar PV and wind power for new bulk electricity generation.

Furthermore, the RPS scenarios give us a glimpse of what the generation would look like if a government imposed climate agenda with a renewable electricity target for 2030 is adopted. In the case of Menorca, higher RPS targets are met mainly by adding more onshore wind turbines, which, based on the modelled parameters, have a higher capacity factor than solar PV: 34% and

26% respectively. Batteries also take a much more prevalent role in the RPS scenarios, supplying as much as 18% of total electricity for a 95% RPS target.

4.5.3. Carbon emissions

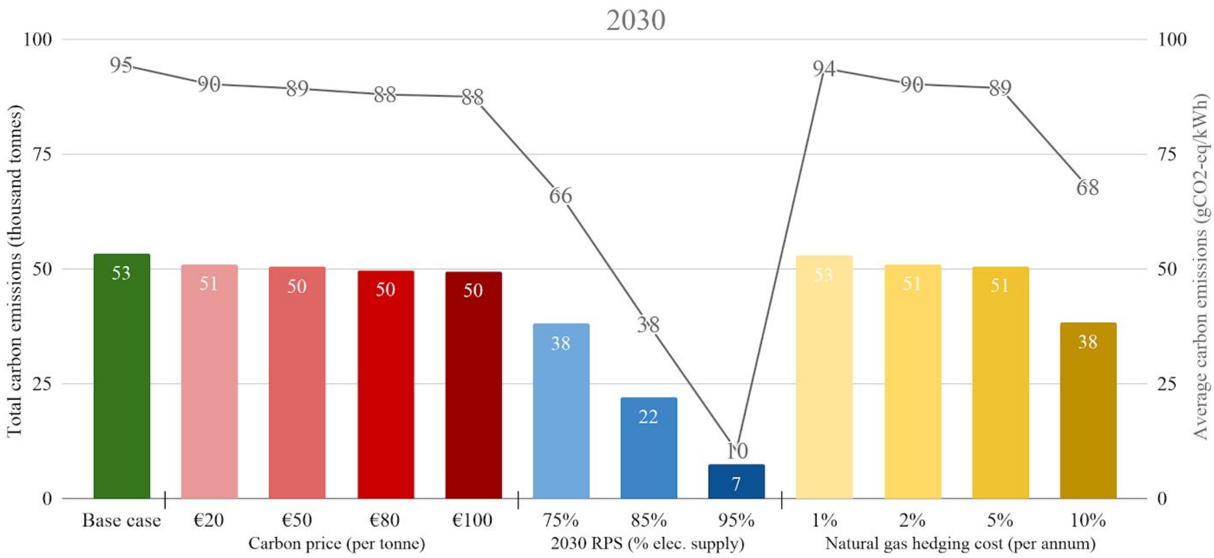

Figure 48 - Comparison of electricity-related carbon emissions in 2030 for all scenarios (Elaboration: author)

When looking at electricity related emissions for the year of 2030 alone (Figure 48), there is a noticeable difference between the carbon footprint of each scenario. The base case, which does not include a carbon price nor a renewable mandate and keeps natural gas prices constant, results in the highest level of emissions, at 95 gCO_2-eq/kWh – and yet, it represents a close to 90% reduction from the 826 gCO_2-eq/kWh emitted in 2019 (Figure 33).

The introduction of a carbon price has a limited impact on the power system's carbon footprint. Even at €100 per tonne, emissions drop by only 7% relative to the base case (i.e. no carbon price). Similarly, for natural gas hedging costs of up to 5% per annum, emissions also decrease by less than 10%, whereas for the more extreme scenario of a 10% annual premium to fix gas prices, they fall by nearly 30% (Figure 48).

Lastly, the RPS scenario shows the most dramatic impact on emissions. In the absence of a renewable mandate (i.e. base case) two thirds of electricity generation in 2030 is supplied by renewables, resulting in a total of 53 thousand tonnes of carbon emitted. A 75% RPS target brings emissions down to 38 thousand tonnes, while a 95% renewable mandate slashes the grid's carbon footprint by 87% to 7 thousand tonnes, averaging 10 gCO_2-eq/kWh in 2030 (Figure 48).

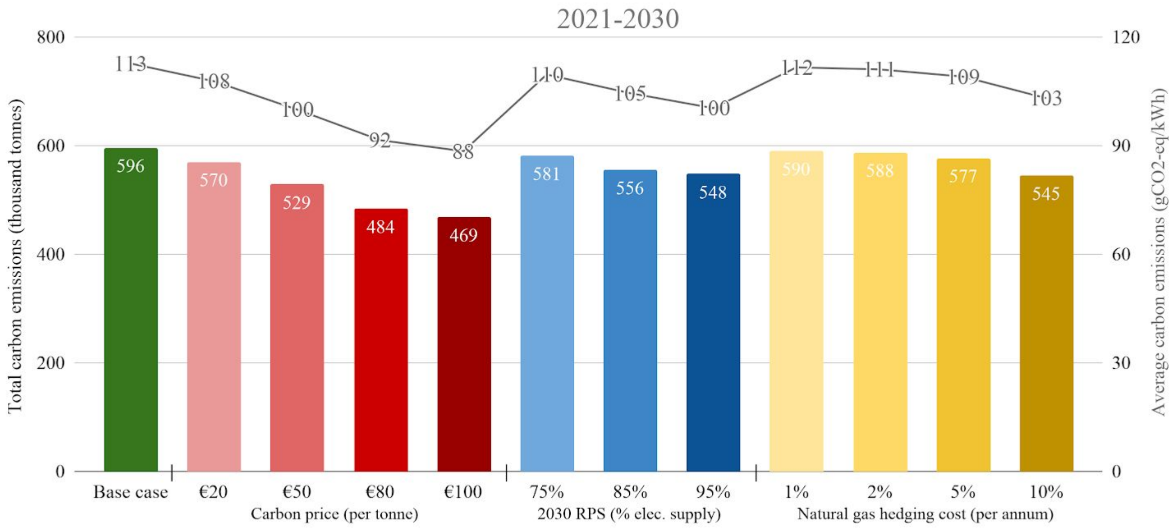

Figure 49 - Comparison of total and average emissions from 2021 to 2030 for all scenarios (Elaboration: author)

Aside from the 2030 emissions produced by each of the scenarios analysed (Figure 48), it is also important to look at the differences in the overall carbon intensity over the entire simulation period, from 2021 to 2030. With much less pronounced differences, emissions results for the 10 years show a different picture in terms of which parameters have the highest impact on the power system's cumulative carbon footprint (Figure 49).

Because the RPS targets are modelled to be met by 2030, a lot of the renewable capacity deployment required to achieve those targets takes place in the beginning of 2030, just before the deadline (Figure 39). While this does result in a cost-optimized system (i.e. lowest NPV) while meeting the RPS targets, it also shifts the emissions reduction in time, thus having a less significant impact with respect to the full 10-year period (Figure 49).

By contrast, the effectiveness of a carbon price on reducing total emissions is much clearer from a long-term perspective. While the impact of a €100 per tonne carbon price was only 6% for 2030 alone (Figure 48), over the ten years of simulation, it yielded the highest reduction in emissions of all cases, a drop of more than 20% relative to the base case (Figure 49).

It must be noted that although this section focuses on comparing the results of different scenarios modelled for this study, in a global context, an electrical grid with a carbon footprint of about 100 gCO_2-eq/kWh would constitute an incredible improvement for Menorca, especially when considering the island's current dependence on a single fossil-based thermal plant and the challenges of coping with the high variability in demand due to its thriving tourism industry.

4.5.4. Investments and costs

Based on the cost-optimization results for each of the scenarios simulated, it is crucial to assess and compare the investments and costs necessary to implement each one. There are several metrics used to analyse costs such as the cost per unit of power ($/MW) for generators, the cost per unit of energy capacity ($/MWh) for storage technologies, the levelized cost of electricity (LCOE) – which basically measures the cost per unit of electricity of a given technology over its useful lifetime – among many others. From a finance perspective, the payback period, internal rate of return (IRR) and net present value (NPV) are some of the most widely used parameters.

Each one of these metrics has its intended applications and intrinsic limitations, making their relevance subject to the specifics of the context being analysed. Fundamental variables needed to calculate the required investments and respective costs of a given power system: interest and discount rates, electricity and fuel prices, future cost curves for each technology, project lifetime, engineering and procurement, legal and permitting, etc; all affect the economics of a project. Hence, it is paramount to understand the applicability and possible inaccuracies of each metric in order for relevant and insightful comparisons to be made.

Against this backdrop, a few economical considerations shall be presented to allow for a more thorough interpretation of the results of this study. The two metrics assessed for each of the scenarios are the net present value (with 2021 as the base year) and the average real cost of electricity (€/MWh). The NPV is especially important since it is the variable for which the cost-optimization algorithm is solving for[99], while the average real cost of electricity gives an idea of how expensive is the electricity being generated throughout the 10 years modelled.

It must be noted that a key limitation of this study is the fact that the 10-year time period simulated does not match the lifetime of the energy technologies being considered, which, under normal circumstances, are likely to be operational for much longer than a decade (Table 2). This implies that investments (i.e. CAPEX) are not amortized throughout the full expected life of each project[100], thus resulting in higher costs than what is likely to be realized in practice. Consequently, the calculation of metrics such as the LCOE over a 10-year period yields

[99] Recall that the objective function is defined to find the power system with the minimum NPV (i.e. lowest cost).

[100] Because different energy technologies have different expected lifetimes, it is unfeasible to normalize the study-period to match the useful life of each and every project, making such analysis impractical from a power system modelling perspective.

inaccurate and meaningless results. Moreover, the payback period and internal rate of return, in addition to the project lifetime mismatch, also require the implementation of a power market model with wholesale electricity prices so that the cash flows of each project can be calculated, which falls outside the scope of this study. Thus such metrics are not included here.

Given these limitations and the fact that the primary objective of this analysis is to identify the lowest-cost solution from the perspective of a centrally planned and integrated power system, investment and cost considerations ought to focus on comparisons and parallels of the solutions found for each scenario. Emphasis is, therefore, placed on the impact of different parameters on the NPV and average real cost of electricity[101] as the time horizon and demand conditions are kept consistent across all simulated cases. This way the results can be assessed and interpreted more objectively and pragmatically.

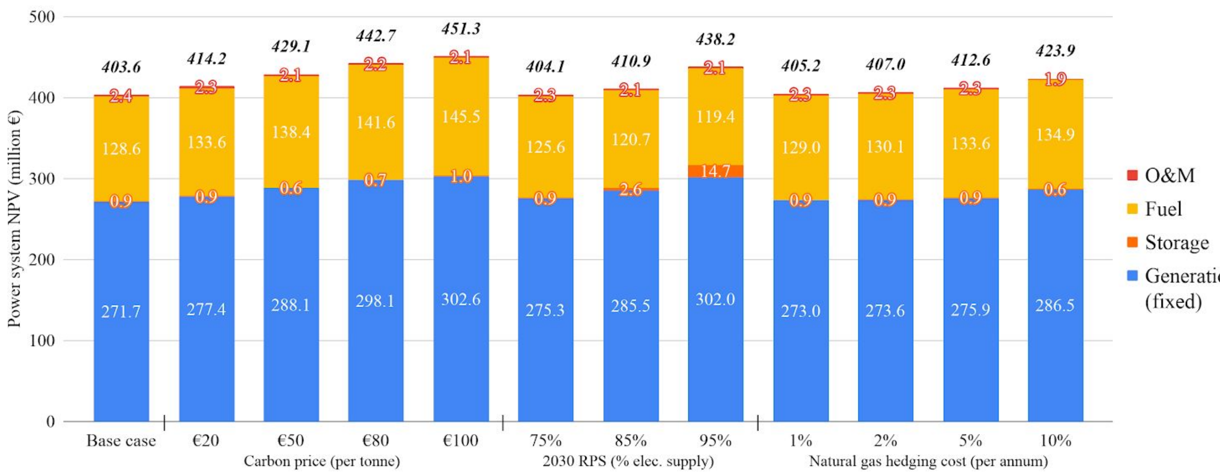

Figure 50 - NPV (base year 2021) of cost-optimum power system for all scenarios (Elaboration: author)

Despite the significant differences between the imposed conditions for each of the cases simulated, the net present value of the lowest-cost power system capable of meeting Menorca's (projected) electricity demand from 2021-2030 varies by about 12% between the least and most costly scenarios. The base case presents the lowest NPV, at 403.6 million euros, while a carbon price of €100 per tonne yields the highest NPV, 451.3 million euros (Figure 50).

The fixed costs of new power plants (CAPEX for the deployment of generating capacity) takes the highest share of investments, ranging between 65% and 70% of the total. The NPV of the installation costs of storage projects (i.e. batteries) stays below 1 million euros for all but the

[101] The annual real cost of electricity is calculated as the ratio between the real (non-discounted) yearly costs (both fixed and variable) and the amount of electricity supplied by the system during that respective year.

95% RPS mandate scenario, which requires a close to 15 million euro investment for the installation of a 20 MW battery with 80 MWh of storage capacity. OPEX is divided into two categories: fuel and operation and maintenance (O&M). Fuel costs represent the second largest share of the total NPV, varying between 27% (for the 95% RPS scenario) and 32% for carbon prices above €80 per tonne. Finally, O&M makes up about 0.5% of costs.

To put the NPV results into perspective, they must also be analysed in terms of the amount of electricity being generated by each specific power system, and further contextualized with the current costs of generating electricity in Menorca. Figure 51 shows the average real cost of electricity and the total net present value for each of the twelve scenarios modelled.

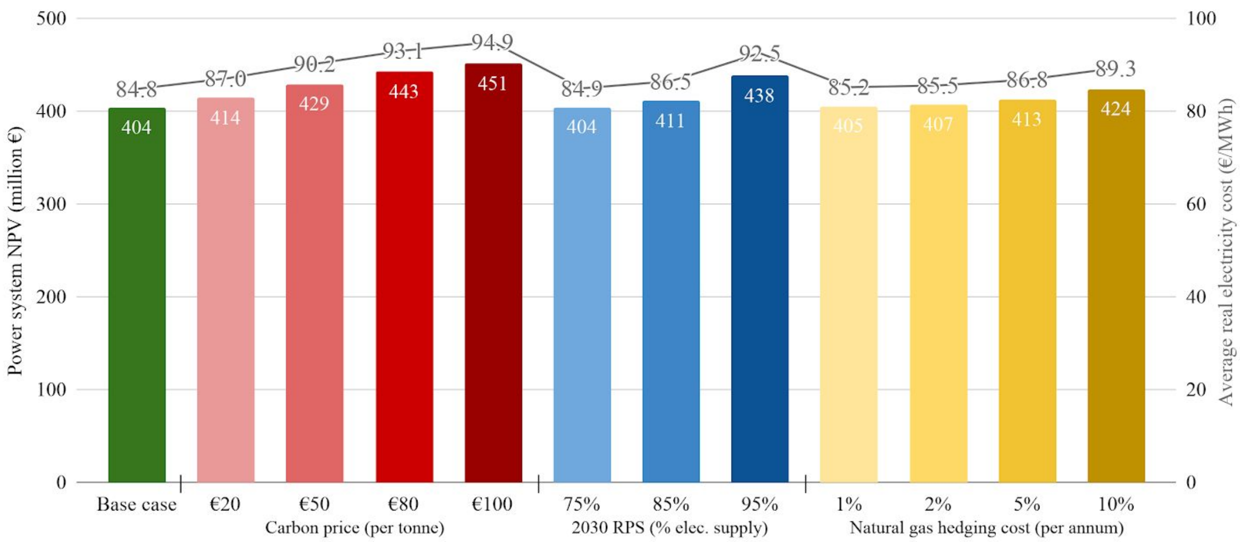

Figure 51 - NPV and average real cost of electricity (2021-2030) for all scenarios (Elaboration: author)

Because the simulated demand is the same across all scenarios, the amount of power generated over the 10 years is almost identical – with a few variations related to losses incurred by charge and discharge processes of storage technologies (i.e. batteries). Therefore the average real cost per megawatt-hour is closely correlated with the NPV of each power system (Figure 51).

The cost-optimum power system for the base case, which has two thirds of generated electricity coming from renewables in 2030 (Figure 30) is only €0.10/MWh cheaper than the 75% RPS scenario. By contrast, to increase the participation of renewables from 75% to 85% by 2030, the average cost goes up by €1.60/MWh, and to go from 85% to 95% renewable generation, the jump in price is €6.00/MWh (Figure 51). The marginal cost of integrating intermittent renewables to Menorca's grid becomes increasingly more expensive at levels beyond 65-70%.

This non-linear growth in electricity costs as a function of the share of renewables (i.e. solar PV and wind power) highlights the difficulties of coping with growing amounts of intermittent (non-dispatchable) sources in the electrical network. Every additional megawatt of solar or wind power added to the system has the same generation profile as existing plants of the same technology, degrading the benefit of the marginal unit of renewable electricity supplied to the grid (i.e. cannibalization effect). This makes the deployment of storage technologies that can efficiently shift generation in time – such as batteries – a crucial enabler for the development of a power system with a (very) high penetration of intermittent renewables.

From a broader perspective, the electricity costs displayed in Figure 51 depict a system with a rather expensive megawatt-hour[102] when compared to, for example, the Spanish peninsular system, which had an average electricity (spot) price of €49.44/MWh from 2015 to 2019 [112]. However, such an assessment misses the point of the analysis herein presented in a major way. A system with high penetration of solar and wind power is heavy on CAPEX and low on OPEX, since these are capital intensive technologies that require high initial investment to be deployed but have zero fuel costs. As a consequence, the economics of renewable projects are closely correlated with the cost of capital and the lifetime over which the invested capital is amortized.

As previously mentioned, the NPV and average real cost of electricity shown are only amortizing investments and costs over the ten years of operation modelled and simulated (2021-2030), despite the fact that the generating assets deployed during this period for each scenario are likely to last for several years beyond 2030[103].

[102] From a contextual point of view, even the high average real costs over a 10-year time horizon, still represents a major improvement over the current situation in the Balearic Islands, which had an average electricity generation price of €118.48/MWh from 2015 to 2019 [112]. This further emphasises the current lack of competitiveness of the Balearic power system.

[103] A quick and conservative calculation ought to make this point clear: if we consider that for any of the scenarios modelled, the final power system of 2030 can continue to generate electricity with a 5% annual performance degradation for each of the following ten years (until 2040), and that CAPEX represents approximately two thirds of the total system's cost (Figure 50), leaving one third as recurrent operational expenditures related to fuel and O&M; then the average real cost of electricity from 2021 to 2040 would be about €62.00/MWh for the base case and lower than €70.00/MWh for all scenarios considered.

Conclusions

The overall picture painted by the cost-optimizations simulated show solar PV and wind power as the cheapest sources of new generation, reaching a combined penetration level of more than two thirds of total electricity supply by 2030 for all scenarios analyzed. Interestingly, onshore wind power is the most cost-efficient of the two, mainly due to a higher capacity factor when compared to solar PV, 34% and 26% respectively.

Such high participation of non-dispatchable sources drastically changes the operation of the electrical network. Intermittent renewables mean a cleaner grid and lower dependence on fossil-fuels, but also the need for a higher level of integration and coordination between different power technologies.

The reliability of Menorca's electrical grid and its ability to successfully integrate high levels of renewable energy during the next decade is highly dependent on the availability of dispatchable and controllable sources. For Menorca, these come in three main forms: interconnectivity via submarine transmission cables, fossil-based generation with thermal power plants and storage technologies that can shift solar or wind power generation in time to match demand.

When considering a centrally planned lowest-cost power system, Menorca's currently outdated and centralized arrangement based on diesel and fuel-oil generators from the GESA thermal power plant gives place to a system dominated by solar PV and onshore wind power. To cope with their intermittency, the existing sea-cable connecting Menorca to Mallorca plays a crucial role, delivering power to the grid whenever not enough solar or wind generation is available. In the absence of a renewable mandate, the interconnection supplies between 25-30% of total electricity by 2030. However, the existing 35 MW sea-cable alone is not enough to cope with the variability of renewables at all times, especially given the high seasonal fluctuation in demand during the summer months, when tourists flock to the island virtually doubling the peak demand.

Open-cycle natural gas turbines (OCGTs) are seen as the next most-competitive type of dispatchable generation, ensuring the continuous supply of power even in adverse weather conditions, playing a key role in the regulation and operation of Menorca's electrical network. Although natural gas represents less than 10% of the total annual electricity supply for all scenarios considered, it offers some important benefits to the system. As synchronous generators, OCGTs can provide inertia and essential ancillary services to the grid, such as frequency and voltage regulation. In addition, their flexibility due to fast ramp-up and ramp-down capabilities improve the electrical network's stability, aiding in the integration of intermittent renewables and allowing for an efficient and reliable operation of the system.

Lithium-ion batteries, the only energy storage technology considered, are modelled with a total cost reduction of 48% by 2030. Despite this steep experience curve, they still have a fairly limited participation in a cost-optimized and centrally planned system, supplying less than 1% of Menorca's annual electricity needs in all but the RPS scenarios. For the 75% and 85% RPS cases, batteries supply approximately 2% and 3% of total electricity by 2030, respectively. The much more stringent 95% RPS target does push batteries to a much more prominent role, displacing the use of the sea-cable and natural gas turbines by storing and releasing enough excess renewable energy to account for about 18% of the total electricity supply in 2030.

Islands present a series of unique characteristics and constraints for the development of a robust and reliable power system. The limited availability of resources impacts the viability of different power generating technologies, from scarce land for the construction of solar farms, to the high cost of importing fuels such as natural gas. Menorca's special status as an UNESCO biosphere reserve combined with the high levels of awareness of the local population regarding ecological and environmental preservation requires continuous communication and coordination between stakeholders to ensure a smooth transition to clean and sustainable energy sources.

While the 85% renewable energy target proposed by the local government symbolizes its strong support for a greener power sector, investments and capital for the execution of new projects require a pragmatic and market oriented approach supported by a clear legislative landscape. The next decade is likely to be one of fundamental changes for the energy industry, putting into question old industry paradigms and pushing companies and legislators to work together to quickly respond to the needs and desires of consumers. Menorca is in a unique position to show the world what the power system of the future can and should look like. Such deep structural changes will require the private and public sectors to work together to completely redesign the island's electric grid to not only tackle climate change and local air pollution, but also improve energy access and promote economic development for all residents of the island.

Budget

The full development of the study herein presented involved a total budget of €73, used for the author to perform a single visit to Menorca from February 19th to February 20th, 2020. The amount covered a round-trip flight from Barcelona (IATA: BCN) to Mahón (IATA: MAH) and accomodation for one night. Such costs were covered by the author with personal funds.

The open-source software package *Switch 2.0* was used to build the computational model for the techno-economic analysis carried out. Furthermore, all the simulations were performed on the author's personal computer. Therefore, no additional costs were incurred by the study.

Environmental Impact

Despite representing a theoretical assessment of what a cost-optimized power system for Menorca would look like in the next decade, the work developed in this study aims to serve as a benchmark against which local authorities and relevant stakeholders can assess energy projects and climate roadmaps going forward. The computational model together with all the techno-economic parameters utilized shall remain fully accessible to the general public for adaptation and reuse. This ought to allow for the model to be updated as continuous technological and market developments bring about new information and different data sets.

An objective and unbiased approach is deliberately adopted (including the implementation of several scenarios) to ensure the study yields pragmatic results that can be used and referenced by relevant actors working on Menorca's power system. As such, the work presented here may help accelerate the adoption of renewable energy technologies such as solar photovoltaic and wind power, given their demonstrated potential to reduce electricity costs, increase the electrical grid's reliability and reduce its carbon footprint.

Menorca's high dependency on fossil fuels for power generation, most notably diesel and fuel-oil, is currently at odds with the government's climate agenda and the island's status as an UNESCO biosphere reserve. Moreover, the proximity of the main thermal power plant (GESA) to the capital city of Mahón has raised concerns among local citizens due to the high levels of air pollution in the region.

Despite the presence of strong and influential corporate interests within Manorca's energy sector, the results of the techno-economic analysis demonstrate how a transition to a cleaner and more sustainable energy mix is aligned with an efficient allocation of capital. A cost-optimum power system based on solar PV and onshore wind power, complemented by natural gas turbines and the existing Mallorca-Menorca sea-cable, is shown to reduce electricity-related carbon emissions by at least 85%. In addition, a switch from heavy fossil fuels (i.e. diesel and fuel-oil) to cleaner and higher quality ones (i.e. natural gas) has the potential to reduce NOx and SOx emissions by more than 80%, while also significantly lowering the levels of particulate matter in the air [113][114].

The ambitious goals put forward by the Menorcan government in the *Estratègia Menorca 2030* roadmap may be supported and further refined based on the results herein presented. Menorca's high electricity-related carbon emissions and air pollution levels are the two main areas that can be substantially improved should the public and private sectors work together to promote efficient market driven solutions that increase competitiveness while improving energy security, public participation and environmental sustainability.

Acknowledgments

2020 has been an extremely unusual year as the COVID-19 global pandemic wreaks havoc worldwide, completely disrupting the social fabric that keeps human civilization moving forward. As I write these words, more than 1.1 million people have died from the coronavirus, while many more have lost their jobs and, with it, their hope for a better future.

As I reflect on the current state of affairs, I can't help but feel extremely privileged and grateful for being able to conclude the study presented in this report, which represents my master thesis research paper and marks the end of a journey that began over two years ago when I decided to pursue a master's degree in sustainable energy engineering.

First and foremost, I would like to thank my family – my parents and my brother – for their unconditional love and support, every step of the way. I would also like to leave a special note of gratitude to *EIT InnoEnergy*, for admitting me to the *Master's in Sustainable Energy Systems* and, most importantly, for giving me the opportunity to experience two incredible and unforgettable years in Europe.

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Finally, I could not leave out two of the most loyal and resourceful "friends" that have been with me throughout this entire journey. Thank you *Google* and *Wikipedia* for making this possible!

Sincerely,

Gustavo Gomes Pereira

Bibliography

[1] "Archivo:Revolucion industria.jpg." [Online]. Available: https://es.wikipedia.org/wiki/Archivo:Revolucion_industria.jpg

[2] "Industry 4.0 - The Fourth Industrial Revolution - Industrial e-Cart - Global Platform for Industrial Demand & Supply," Sep. 23, 2018. [Online]. Available: https://industrialecart.com/blog/industry-4-0-the-fourth-industrial-revolution/

[3] L. Sweetlove, "Number of species on Earth tagged at 8.7 million," *Nature*, Aug. 2011, doi: 10.1038/news.2011.498.

[4] J. T. L. Kenneth J. Locey, "From the Cover: Scaling laws predict global microbial diversity," *Proc. Natl. Acad. Sci. U. S. A.*, vol. 113, no. 21, p. 5970, May 2016, doi: 10.1073/pnas.1521291113

[5] "The Future of Petrochemicals." [Online]. Available: https://www.iea.org/reports/the-future-of-petrochemicals

[6] "Data tables – Data & Statistics - IEA." [Online]. Available: https://www.iea.org/data-and-statistics/data-tables

[7] "Data & Statistics - IEA." [Online]. Available: https://www.iea.org/data-and-statistics

[8] "Ocean-Atmosphere CO2 Exchange." [Online]. Available: https://sos.noaa.gov/datasets/ocean-atmosphere-co2-exchange/

[9] US Department of Commerce, NOAA, and Global Monitoring Laboratory, "Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases," Oct. 2005. [Online]. Available: https://www.esrl.noaa.gov/gmd/ccgg/trends/.

[10] "CO_2 in the atmosphere and annual emissions (1750-2019)" [Online]. Available: https://www.climate.gov/sites/default/files/CO2_emissions_vs_concentrations_1751-2019_lrg.gif

[11] "Conference of the Parties (COP)" [Online]. Available: https://unfccc.int/process/bodies/supreme-bodies/conference-of-the-parties-cop

[12] "United Nations Treaty Collection," [Online]. Available: https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27

[13] "Report for Selected Countries and Subjects," Sep. 14, 2006. [Online]. Available: https://www.imf.org/external/pubs/ft/weo/2019/02/weodata/weorept.aspx

[14] "GDP (current US$)." [Online]. Available: http://data.worldbank.org/indicator/NY.GDP.MKTP.CD?year_high_desc=true

[15] "Daily global crude oil demand 2006-2020." [Online]. Available: https://www.statista.com/statistics/271823/daily-global-crude-oil-demand-since-2006/

[16] V. Smil, *Energy and Civilization: A History*. 2018.

[17] "BP Statistical Review of World Energy - June 2018" [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf

[18] V. Smil, Energy Transitions: History, Requirements, Prospects. ABC-CLIO, 2010.

[19] "[No title]." [Online]. Available: https://twitter.com/BillGates/status/941689269768265728

[20] “Data tables – Data & Statistics - IEA.” [Online]. Available: https://www.iea.org/data-and-statistics/data-tables

[21] “Data & Statistics - IEA.” [Online]. Available: https://www.iea.org/data-and-statistics

[22] “Data tables – Data & Statistics - IEA.” [Online]. Available: https://www.iea.org/data-and-statistics/data-tables

[23] “World carbon intensity,” Aug. 08, 2020. [Online]. Available: https://www.worldenergydata.org/

[24] “New Energy Outlook 2019.” [Online]. Available: https://about.bnef.com/new-energy-outlook/

[25] “A Decade of Renewable Energy Investment, Led by Solar, Tops USD 2.5 Trillion,” Sep. 06, 2019. [Online]. Available: https://about.bnef.com/blog/decade-renewable-energy-investment-led-solar-tops-usd-2-5-trillion/

[26] “The island of Menorca celebrates its 20th anniversary as a UNESCO Biosphere Reserve,” Oct. 07, 2013. [Online]. Available: https://en.unesco.org/news/island-menorca-celebrates-its-20th-anniversary-unesco-biosphere-reserve

[27] Contributors to Wikimedia projects, “Wikimedia Commons,” Sep. 07, 2004. [Online]. Available: https://commons.wikimedia.org/wiki/Main_Page

[28] “Residual fuel oil.” [Online]. Available: http://www.mckinseyenergyinsights.com/resources/refinery-reference-desk/residual-fuel-oil/

[29] “Menorca’s Second Energy Transition” [Online]. Available: http://www.ime.cat/WebEditor/Pagines/file/DEM%20La%20segona%20transici%C3%B3%20(ANGL%C3%88S).pdf

[30] “Población por islas y sexo.” [Online]. Available: https://www.ine.es/jaxiT3/Datos.htm?t=2910#!tabs-tabla

[31] “Archivo:Minorca municipalities es.svg - Wikipedia, la enciclopedia libre.” [Online]. Available: https://es.wikipedia.org/wiki/Archivo:Minorca_municipalities_es.svg

[32] Redaktion und Team KJA-NG NaaniiGlobal and Equipo editorial / periodistas / journalists / Management de Naanii Global, “NAANII GLOBAL Quality & Luxury Family Lifestyle - MAGAZIN ‘en Vogue’-.” [Online]. Available: http://www.naanii.es/blog/?id=lp4jy014

[33] Hosteltur, “Menorca ha recibido este verano un 10,3% más de turistas españoles.” [Online]. Available: https://www.hosteltur.com/109847_el-mercado-domestico-ha-crecido-un-103-este-verano-en-menorca.html

[34] “Seguimiento de la demanda de energía eléctrica.” [Online]. Available: https://demanda.ree.es/visiona/baleares/menorca/total

[35] “Wayback Machine.” [Online]. Available: https://web.archive.org/web/20101002182150/http://www.ree.es/seie/pdf/mapa_transporte_balear_2009_v2.pdf

[36] J. Gilabert, “El sistema eléctrico ya acumula un gasto extra de 20 millones por la falta de cable.” Nov. 03, 2019. [Online]. Available: https://www.menorca.info/menorca/local/2019/11/03/670279/sistema-electrico-acumula-gasto-extra-millones-por-falta-cable.html

[37] “Menorca’s First Energy Transition.” [Online]. Available: http://www.ime.cat/WebEditor/Pagines/file/Menorca%27s%20first%20energy%20transition.pdf

[38] “Documento Rómulo 2013.” [Online]. Available: https://www.ree.es/sites/default/files/downloadable/monograficoromulo.pdf

[39] “Red Eléctrica de España - Unique projects.” [Online]. Available: https://www.ree.es/en/activities/unique-projects

[40] "La segunda transición energética de Menorca." [Online]. Available: http://www.ime.cat/publicacions/llistat.aspx?Tipo=DDEM

[41] OECD, "Sulphur oxides (SOx) and nitrogen oxides (NOx) emissions," pp. 26–29, Dec. 2013. [Online]. Available: https://www.oecd-ilibrary.org/environment/environment-at-a-glance-2013/sulphur-oxides-so-and-nitrogen-oxides-no-emissions_9789264185715-7-en;jsessionid=e-AQu1XepjIfZYMkLfBz8ew6.ip-10-240-5-71

[42] "Air pollution statistical fact sheet 2013." [Online]. Available: https://www.eea.europa.eu/themes/air/air-pollution-country-fact-sheets/spain-air-pollutant-emissions-country-factsheet

[43] "CO2 Intensity of Electricity Generation," Feb. 13, 2020. [Online]. Available: https://www.eea.europa.eu/data-and-maps/data/co2-intensity-of-electricity-generation

[44] "Database - Eurostat." [Online]. Available: https://ec.europa.eu/eurostat/data/database

[45] "Red Eléctrica de España." [Online]. Available: https://www.ree.es/en/datos/todate

[46] OBSAM, "La ineficiència de la central tèrmica de Maó implica unes emissions molt elevades per cada unitat d'energia generada," Apr. 20, 2020. [Online]. Available: https://www.obsam.cat/la-ineficiencia-de-la-central-termica-de-mao-implica-unes-emissions-molt-elevades-per-cada-unitat-denergia-generada/

[47] "The European Power Sector in 2018" [Online]. Available: https://www.agora-energiewende.de/fileadmin2/Projekte/2018/EU-Jahresauswertung_2019/Agora-Energiewende_European-Power-Sector-2018_WEB.pdf

[48] "The European Power Sector in 2019." [Online]. Available: https://www.agora-energiewende.de/fileadmin2/Projekte/2019/Jahresauswertung_EU_2019/A-EW_EU-Annual-Report-2019_Slide-Deck.pdf

[49] A. Vaughan, "Balearic Islands bank on their sun to kickstart power drive," May 04, 2018. [Online]. Available: http://www.theguardian.com/business/2018/may/04/balearic-islands-bank-on-sun-to-kickstart-power-drive-renewables

[50] "Switch 2.0: A modern platform for planning high-renewable power systems," *SoftwareX*, vol. 10, p. 100251, Jul. 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352711018301547?via%3Dihub

[51] A. Laurent, Understanding Open Source and Free Software Licensing. "O'Reilly Media, Inc.," 2004.

[52] "Switch 2.0 Tutorial: Pre-Tutorial Setup." [Online]. Available: https://github.com/switch-model/switch_tutorial/raw/master/Switch_Pre-Tutorial_Instructions.pdf

[53] J. Johnston, R. Henriquez-Auba, B. Maluenda, and M. Fripp, "Switch 2.0: A modern platform for planning high-renewable power systems," SoftwareX, vol. 10. p. 100251, 2019, doi: 10.1016/j.softx.2019.100251.

[54] "La segona transició energètica de Menorca." [Online]. Available: http://www.ime.cat/WebEditor/Pagines/file/DEM%20La%20segona%20trancisi%C3%B3%20....%20CATAL%C3%80.pdf

[55] "Coronavirus disease (COVID-19) – World Health Organization." [Online]. Available: https://www.who.int/emergencies/diseases/novel-coronavirus-2019

[56] "New Energy Outlook 2019." [Online]. Available: https://about.bnef.com/new-energy-outlook/

[57] "The First Phase of the Transition is About Electricity, Not Primary Energy," Jan. 28, 2020. [Online]. Available: https://about.bnef.com/blog/the-first-phase-of-the-transition-is-about-electricity-not-primary-energy/

[58] "Scale-up of Solar and Wind Puts Existing Coal, Gas at Risk," Apr. 28, 2020. [Online]. Available: https://about.bnef.com/blog/scale-up-of-solar-and-wind-puts-existing-coal-gas-at-risk/

[59] "Lazard's Levelized Cost of Energy Analysis–Version 8.0" [Online]. Available: https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf

[60] S. J. Ericson and D. R. Olis, "A Comparison of Fuel Choice for Backup Generators." 2019, doi: 10.2172/1505554.

[61] "Levelized Cost of Electricity Renewable Energy Technology - March 2018." [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

[62] S. Sabol, *Case Studies in Mechanical Engineering: Decision Making, Thermodynamics, Fluid Mechanics and Heat Transfer*. John Wiley & Sons, 2016.

[63] "2019 Costs and Technical Parameter Review." [Online]. Available: https://www.aemo.com.au/-/media/Files/Electricity/NEM/Planning_and_Forecasting/Inputs-Assumptions-Methodologies/2019/Aurecon-2019-Cost-and-Technical-Parameters-Review-Draft-Report.PDF

[64] A. Arvesen and E. G. Hertwich, "Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs," Renewable and Sustainable Energy Reviews, vol. 16, no. 8. pp. 5994–6006, 2012, doi: 10.1016/j.rser.2012.06.023.

[65] M. Parol, "Cable links designing in HVAC and HVDC submarine power grids - selected issues," ELECTROTECHNICAL REVIEW, vol. 1, no. 3, pp. 9–15, Mar. 2019.

[66] "Trabajos de mantenimiento en líneas y subestaciones de Red Eléctrica." [Online]. Available: https://www.ree.es/sites/default/files/downloadable/mantenimiento.pdf

[67] W. J. Cole and A. Frazier, "Cost Projections for Utility-Scale Battery Storage." 2019, doi: 10.2172/1529218.

[68] "Menorca's Second Energy Transition." [Online]. Available: http://www.ime.cat/WebEditor/Pagines/file/DEM%20La%20segona%20transici%C3%B3%20(ANGL%C3%88S).pdf

[69] M. Á. Noceda, "Red Eléctrica plantea duplicar las conexiones en Baleares para evitar apagones," Nov. 04, 2019. [Online]. Available: https://elpais.com/economia/2019/11/04/actualidad/1572887647_090241.html

[70] "Oil Bulletin Prices." [Online]. Available: https://ec.europa.eu/energy/observatory/reports/Oil_Bulletin_Prices_History.xlsx

[71] "Weekly Oil Bulletin," Jan. 07, 2019. [Online]. Available: https://ec.europa.eu/energy/data-analysis/weekly-oil-bulletin_en

[72] "Data Explorer." [Online]. Available: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en

[73] "[No title.]" [Online]. Available: https://www.esios.ree.es/es/analisis/573?vis=1&start_date=01-01-2017T00%3A00&end_date=31-12-2020T23%3A50&compare_start_date=01-01-2016T00%3A00&groupby=year&compare_indicators=10244,578&geoids=8743

[74] "SAS Output." [Online]. Available: https://www.eia.gov/electricity/annual/html/epa_08_01.html

[75] "Capital Cost Estimates for Utility Scale Electricity Generating Plants." [Online]. Available: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf

[76] "Lazard's Levelized Cost of Energy Analysis–Version 13.0" [Online]. Available: https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

[77] "2019 ATB Cost and Performance Summary." [Online]. Available: https://atb.nrel.gov/electricity/2019/summary.html

[78] "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2020." [Online]. Available: https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf

[79] "Red Eléctrica finaliza el tendido submarino del enlace eléctrico que unirá las islas de Menorca y Mallorca." Nov. 21, 2019. [Online]. Available: https://www.ree.es/es/sala-de-prensa/actualidad/notas-de-prensa/2019/11/red-electrica-finaliza-el-tendido-submarino-del-enlace-electrico-que-unira-las-islas-de-Menorca-y-Mallorca

[80] "Red Eléctrica pone en servicio el nuevo enlace eléctrico submarino entre Menorca y Mallorca." Jun. 18 2020. [Online]. Available: https://www.ree.es/es/sala-de-prensa/actualidad/especial/2020/06/red-electrica-pone-en-servicio-el-nuevo-enlace-electrico-submarino-entre-mallorca-menorca#

[81] "Offshore Electricity Grid Implementation in the North Sea." [Online]. Available: http://www.northseagrid.info/sites/default/files/NorthSeaGrid_Final_Report_Annexes.pdf

[82] N. B. Negra, J. Todorovic, and T. Ackermann, "Loss evaluation of HVAC and HVDC transmission solutions for large offshore wind farms," Electric Power Systems Research, vol. 76, no. 11, pp. 916–927, Jul. 2006.

[83] "Battery Storage." [Online]. Available: https://atb.nrel.gov/electricity/2019/index.html?t=st

[84] "Lazard's Levelized Cost of Storage Analysis–Version 5.0" [Online]. Available: https://www.lazard.com/media/451087/lazards-levelized-cost-of-storage-version-50-vf.pdf

[85] K. Galbraith, "Just how accurate are oil price predictions?" Nov. 10, 2017. [Online]. Available: https://materials-risk.com/just-accurate-oil-price-predictions/#:~:text=The%20answer%20was%20clearly%20no,by%20an%20average%20of%2030%25.

[86] M. Lynch, "Forecasting The Oil Price For Fun And Profit (But Not Accuracy)," *Forbes*, Mar. 05, 2019. [Online]. Available: https://www.forbes.com/sites/michaellynch/2019/03/05/forecasting-the-oil-price-for-fun-and-profit-but-not-accuracy/

[87] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission," Jan. 11, 2016. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/#HR

[88] I. Pinedo, "PVGIS users manual," Jun. 25, 2019. [Online]. Available: https://ec.europa.eu/jrc/en/PVGIS/docs/usermanual

[89] "JRC Photovoltaic Geographical Information System (PVGIS) - European Commission," Jan. 11, 2016. [Online]. Available: https://re.jrc.ec.europa.eu/pvg_tools/en/#HR

[90] "Roughness and Wind Shear." [Online]. Available: http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/shear.htm

[91] S. Ali, S.-M. Lee, and C.-M. Jang, "Statistical analysis of wind characteristics using Weibull and Rayleigh distributions in Deokjeok-do Island – Incheon, South Korea," Renewable Energy, vol. 123. pp. 652–663, 2018, doi: 10.1016/j.renene.2018.02.087.

[92] G. M. Masters, "Renewable and Efficient Electric Power Systems." 2004, doi: 10.1002/0471668826.

[93] Tutiempo Network, S. L, "ICAO: LEMH." [Online]. Available: https://www.tutiempo.net/registros/lemh/1-enero-2019.html

[94] Vestas-www. vestas.com, "V136-3.45 MW®," [Online]. Available: https://www.vestas.com/en/products/4-mw-platform/v136-_3_45_mw#!facts.

[95] L. Bauer, "Vestas V136-3.45." [Online]. Available: https://en.wind-turbine-models.com/turbines/1282-vestas-v136-3.45

[96] T. Corke and R. Nelson, *Wind Energy Design*. CRC Press, 2018.

[97] "Global Wind Atlas." [Online]. Available: https://globalwindatlas.info

[98] "Wind Energy Concepts." http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/stat/unitsw.htm#roughness

[99] "Betz' Law." [Online]. Available: http://xn--drmstrre-64ad.dk/wp-content/wind/miller/windpower%20web/en/tour/wres/betz.htm

[100] "Switch 2.0 Tutorial." [Online]. Available: https://github.com/switch-model/switch_tutorial/raw/master/SwitchTutorial.pdf

[101] V. Quaschning, "Regenerative Energiesysteme," *Regenerative Energiesysteme*. pp. 1–12, 2019, doi: 10.3139/9783446461147.fm.

[102] J. Johnston, R. Henriquez-Auba, B. Maluenda, and M. Fripp, "Switch 2.0: A modern platform for planning high-renewable power systems," SoftwareX, vol. 10. p. 100251, 2019, doi: 10.1016/j.softx.2019.100251.

[103] J. Chappelow, "Discount Rate," Aug. 30, 2020. [Online]. Available: https://www.investopedia.com/terms/d/discountrate.asp

[104] "Levelized Cost of Electricity Renewable Energy Technology - March 2018." [Online]. Available: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/EN2018_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies.pdf

[105] J. Steinbach, and D. Staniaszek "Discount rates in energy system analysis." [Online]. Available: https://www.bpie.eu/wp-content/uploads/2015/10/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf

[106] "Markets Rates & Bonds." [Online]. Available: https://www.bloomberg.com/markets/rates-bonds

[107] "La segunda transición energética de Menorca." [Online]. Available: http://www.ime.cat/WebEditor/Pagines/file/DEM%20La%20segunda%20transici%C3%B3n%20energ%C3%A9tica%20(CASTELL%C3%80).pdf

[108] "Dutch TTF Natural Gas Calendar Month Futures Quotes - CME Group." [Online]. Available: https://www.cmegroup.com/content/cmegroup/en/trading/energy/natural-gas/dutch-ttf-natural-gas-calendar-month.html

[109] "EU Emissions Trading System (EU ETS)," Nov. 23, 2016. [Online]. Available: https://ec.europa.eu/clima/policies/ets_en

[110] "Data Repository." [Online]. Available: https://nea.is/the-national-energy-authority/energy-data/data-repository/

[111] "Data Explorer" [Online]. Available: https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_pc_203&lang=en

[112] "Mercados y Precios" [Online]. Available: https://www.esios.ree.es/es/mercados-y-precios

[113] "Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion," Energy, vol. 57, pp. 412–420, Aug. 2013, doi: 10.1016/j.energy.2013.05.002.

[114] Verbeek, R., G. Kadijk, P. V. Mensch, C. Wulffers, C. V. D. Beemt and F. Fraga. "Environmental and economic aspects of using LNG as a fuel for shipping in The Netherlands." 2011.