Evaluation of the Technical and Economic Feasibility of Carnot Batteries

A case study on the German electrical system

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Sustainable Energy Planning and Management

Master's Thesis

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Abstract:

This study investigates the economic and technical feasibility of Carnot batteries in the German context. The theoretical approach that combines Carbon lock-in and Multi-level perspective theory has shown that there is a window of opportunity for niche technologies such as Carnot to disrupt the system and become institutionalised. In order to do it is necessary to find a viable marketplace. Hence, the application in the power sector was analysed recurring to a methodology that includes the utilisation of EnergyPLAN combined with Matlab. This approach allowed the simulation and optimisation of 21 different pathways. From this analysis, it was possible to conclude that there is a promising perspective for the use of Carnot batteries in the retrofitting of existing coal-fired power plants.

Contents

Preface

This Master Thesis has been developed under the Master's Programme in Urban, Energy and Environmental Planning, specialising in Sustainable Energy Planning and Management at Aalborg Univerity.

Acknowledgments

There are numerous individuals who have significantly contributed to the conclusion of this thesis. Firstly, I would like to take this opportunity to show my gratitude to my supervisor Dr Peter Sorknæs, that had shared his expertise and support.

I would also like to extend my deep appreciation to the other professors, staff, and colleagues who provided support during this journey.

Moreover, I would like to recognise the paramount effort and importance of my family members, attributing them all the merit of the challenges overcome.

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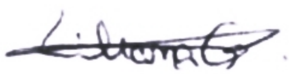

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Chapter 1

Problem Analysis

In order to assess the human impact on earth global temperature, the Intergovernmental Panel on Climate Change (IPCC) has reconstructed global surface temperature changes from paleoclimate archives, as can be seen on the left side of Figure 1.1. It can be understood that some changes in global surface temperature occur as a result of natural effects. For instance, the highest estimated natural temperature increase in the last 100,000 years ranged from 0.2 to 1 Celsius degree caused by slow orbital variations during millenniums. However, it is also seen an unprecedented increase in global temperature throughout the observed time (1850-2020).

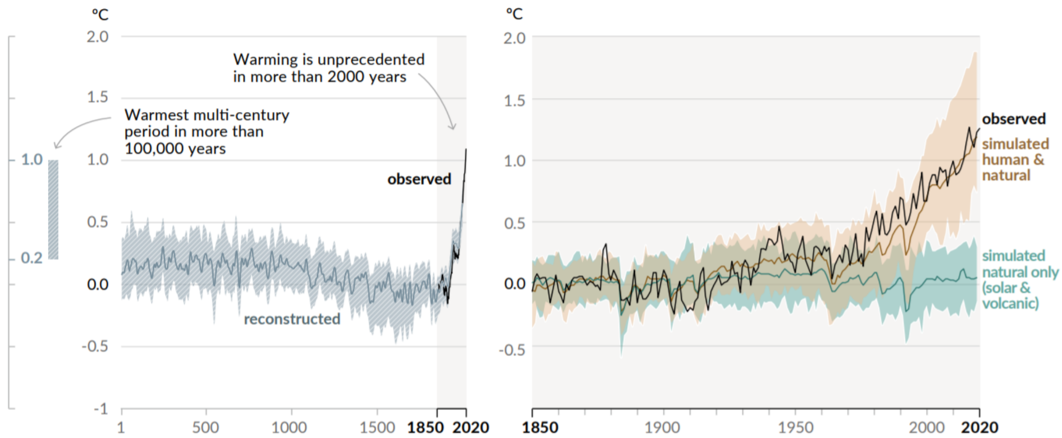

Figure 1.1: GHG emissions reduction in European compatible with Paris Agreement [IPCC, 2021].

During the recent decade, the temperature increase exceeded the warmest multi-century period in 100,000 years. The right side of Figure 1.1 shows the cause of this unparalleled warming by simulating the natural changes (coloured in green) and comparing that results with the observed increase in global temperature (line in black). Doing this possible to quantify and undoubtedly state the nefarious impact of human behaviour. The unnatural emission of greenhouse gases by human activity has disrupted global surface temperature changes. It is foreseen that human-caused temperature increased from 1850 until 2019, varies from 0.8 to 1.3 Celsius degrees. This substantial temperature increase is intensifying the frequency of extreme weather events, such has heatwaves, heavy precipitation, droughts and cyclones [IPCC, 2021]. Therefore, it is crucial to limit the global warming cause by human activity to reduce the present environmental impact that we are causing as a specie.

In the fight against climate change, the Paris Agreement occupies a historical position as the first legally binding agreement between all nations. The intention is to limit global temperature rise to 1.5 Celsius degre es, in comparison to pre-industrialisation times. To successfully achieve this long-term goal, countries have the mission to pertly reduce greenhouse gas emissions to reach a climate-neutral world by 2050 [UNFCCC, 2021].

1.1 Make or break decade

In the interest of limiting the temperature rise to 1.5 Celsius degrees, the IPCC has clearly stated that it is necessary to cut 45% of emissions below 2010 levels by 2030 [IPCC, 2021]. Hence, we as a species have a make or break decade in front of us, where the success of 1.5 C and the long-term goal of carbon neutrality will be put into test. In other words, our impact results from cumulative greenhouse gas emissions, so a fast and continuous emission reduction, or even if a global net zero is achieved by 2050, the emissions emitted before will cause a more extensive temperature increase than 1.5 C. It was been estimated that for 2030 there is a gap of 19 to 23 gigatonnes of carbon dioxide (CO_2) equivalent.

After COP26, including the recent announcement from India, 90% of global emissions were covered by net-zero targets. However, even in the most *optimistic scenario*, shown in Figure 1.2, where all countries would fulfil their net-zero pledges, the global temperature would still rise to 1.8 C.

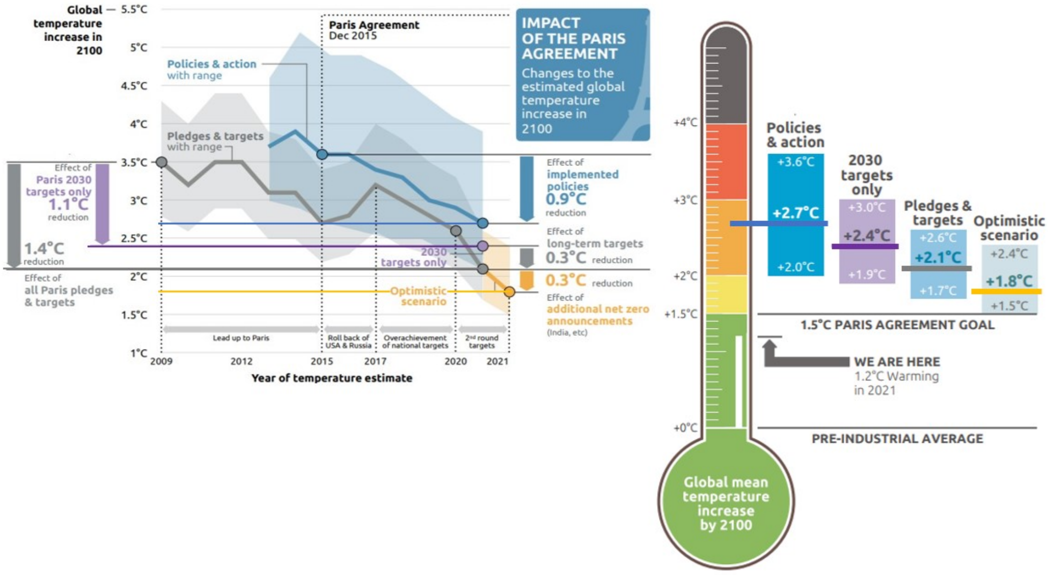

Figure 1.2: The impact of Paris agreement. Own elaboration. Adapted from Climate Action Tracker, 2021.

The case becomes even more problematic when net-zero targets are scrutinised, as the Climate Action Tracker has assessed that only 6% of global emissions are covered with an acceptable net-zero target, namely Chile, Costa Rica, the United Kingdom, and the European Union [Climate Action Tracker, 2021].

The European Union (EU), as one of the about 190 parties to the Paris Agreement, has been prominent in the fight against climate change. The European Commission recently updated the initial commitment under the agreement to reduce 40% of greenhouse gas emissions by 2030 compared to 1990, and the enhanced ambition is now to achieve a reduction of at least 55% [European Commission, 2021]. However, if we exclude Land use, Land use change and Forestry the emission reduction target is 52%. Despite the extra motivation demonstrated, Climate analytics has concluded that the targets of carbon emission reduction are still not compatible with the Paris agreement and only a 62% reduction would be aligned with the 1.5 Celsius goal [Climate Analytics, 2021].

Even though the EU goal is not adequate, to reduce 55% of greenhouse gas emissions by 2030 requires a mammoth decarbonisation in all sectors, in all 27 countries. The particularities of different the EU countries as seen in Figure 1.3.

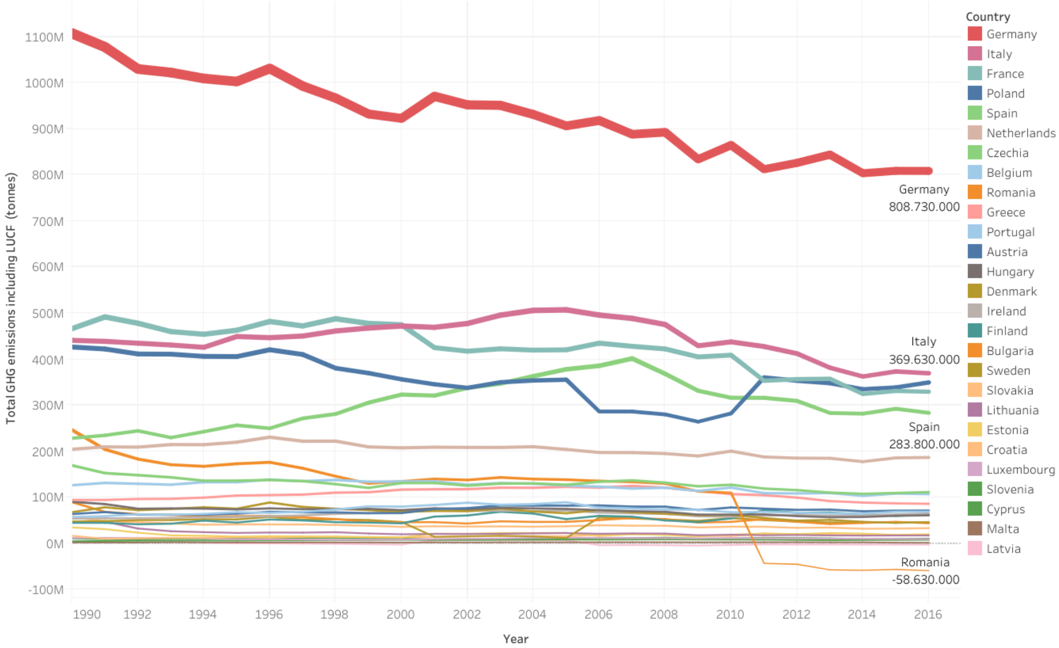

Figure 1.3: European Union total greenhouse gas emissions from 1990 to 2016. Own elaboration. Based on Ritchie and Roser, 2020.

As can be seen in Figure 1.3, the largest amount of greenhouse gases emissions in the European Union is from Germany. The highest emission GHG gases by Germany is related to the most prominent EU population and economy [Climate Analytics, 2021]. While the total GHG German emissions in 2016 have decreased to almost 27% compared to 1990 levels, Germany is still the biggest European emitter [Ritchie and Roser, 2020]. Therefore, it will be chosen as a case study due to the significant challenge and impact of transitioning to a clean energy system.

1.2 German energy transition

The present GHG emission reduction challenge in the different German sectors are represented in Figure 1.4. It is visible that despite the efforts to reduce emissions in the energy sector, energy production is still the major contributor to global warming.

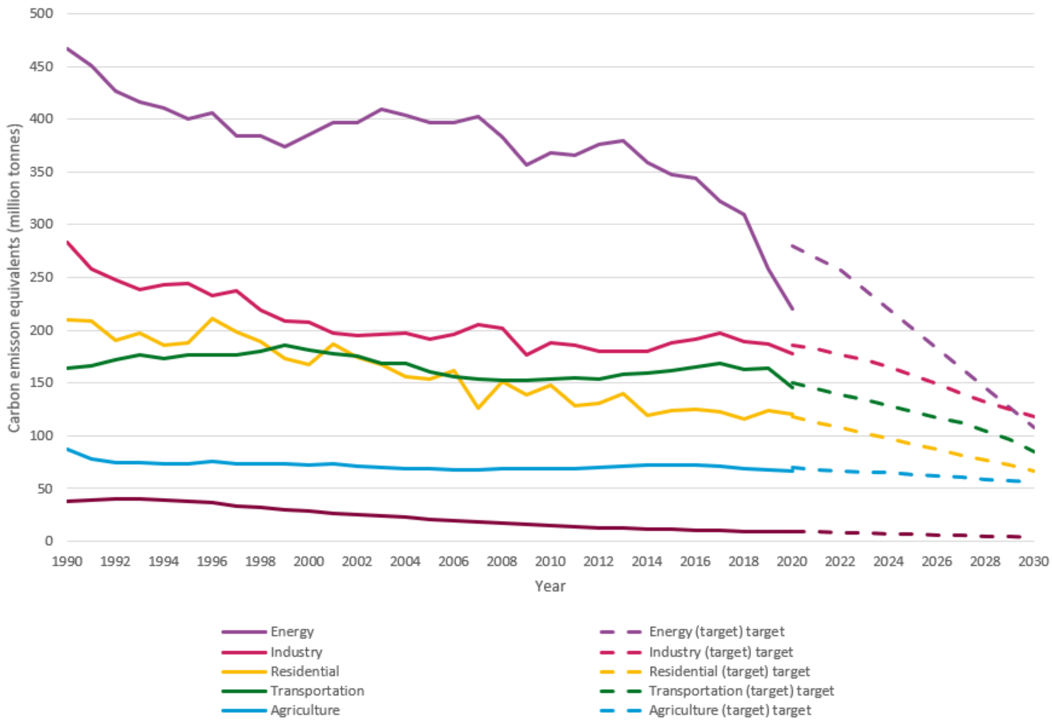

Figure 1.4: German greenhouse gas emissions and targets by sector. Own elaboration. Based on [UBA, 2021].

The high GHG emissions are related to a still considerable German dependency on nuclear energy and fossil fuels that release dangerous carbon dioxide emissions. As seen in Figure 1.5, in 2020, 50% of the electricity was produced by nuclear, gas, and coal. Notwithstanding, this is a notable tipping point where renewable sources alone tend to supply more than half of electricity.

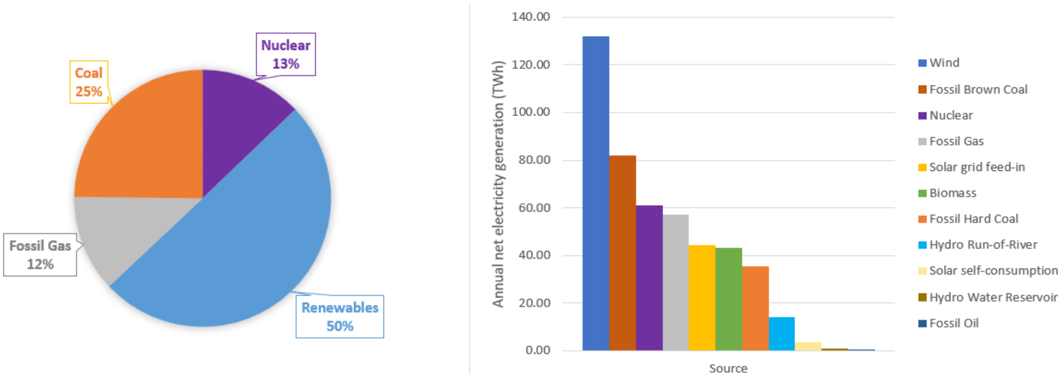

Figure 1.5: German net electricity in 2020. Own elaboration. Based on Frauhoher ISE, 2021a.

Germany has been notorious on the energy transition and has continuously increased renewable energy penetration. However, in order to be aligned with the 1.5 Celsius target, Germany will have to reduce at least 72% of all GHG emissions by 2030. This would mean that, by 2030, the primary energy supply would have to be composed of 42 to 47% of fossil fuels, and 53 to 58% of renewable energy including biomass.

A transition in the power sector aligned with the Paris agreement would require a reduction of at least 92% CO_2 by 2030, compared to 1990 levels [Climate Analytics, 2021]. In order to reduce the emitted carbon dioxide, a new possible mix for the power sector is seen in Table 1.1.

Table 1.1: Power mix compatible with Paris agreement in 2030. Own elaboration. Based on Climate Analytics, 2021 and Frauhoher ISE, 2021a.

	Renewables incl. biomass	**Coal**	**Fossil gas**	**Nuclear**
2020	50%	25%	12%	13%
2030	93-97%	0-1%	3-6%	0%

Logically, a roughly clean power system by 2030 requires a total dominance of renewable, a penetration of at least 93%, and the reduction of fossil fuels dependency. Even though nuclear energy does not emit GHG gases during operation, Germany has announced a nuclear phase-out by 2022 due to the unmanageable risks this technology poses for the environment and humans [BMU, 2021]. Germany has not yet initiated discussions about fossil gas phase out [Climate Analytics, 2021].

In addition, to achieve a 92% cut in emissions, it is paramount to phase out coal-fired plants considering that is the technology that most emits CO**2** equivalent per kWh [IPCC, 2021]. For that reason, Germany has pledged to phase out coal by 2038. However, this target was appointed as too late and insufficient [Climate Analytics, 2021]. Nevertheless, a recent governmental coalition has set to raise the ambition of the previous targets [Koalitionsvertrag Zwischen, 2021].

1.3 German enhanced ambition

The new German government has announced the intention to ideally phase-out coal by 2030, translating into eight-year anticipation concerning the previous target. In order to replace the current coal-fired power plant contribution for clean sources, the renewable share target in electricity production was also accelerated, as seen in Table 1.2.

Table 1.2: German targets towards carbon neutrality. Own elaboration. Based on Frauhoher ISE, 2021a; Koalitionsvertrag Zwischen, 2021.

	2020	New 2030 target	Previous target
Renewable target in electricity (%)	50	80	65
Electricity Demand (TWh/year)	481	680-750	580
Coal-fired power plant capacity (GW)	44	$\sim$0	17
Solar PV capacity (GW)	54	200	100
Onshore wind capacity (GW)	55	100	75
Offshore wind capacity (GW)	8	30	20

Renewable sources would supply 80% of the electricity demand with this new power system configuration. Since the electricity demand is also expected to increase, this would mean that in 2030, up to 600 TWh of electricity demand would come from renewable energies (expected an even higher value due to the low capacity factor related to renewable generation), a significant increase from the approximately 242 TWh in 2020 [Frauhoher ISE, 2021a]. These new targets result in a doubling in the solar PV capacity concerning the previous target and a significant increase in the onshore and offshore wind capacity [Koalitionsvertrag Zwischen, 2021].

The dominance of intermittent renewable sources modifies the operation of the power system and presents new challenges such as guaranteeing grid stability, preventing grid congestion and energy curtailment, and ensuring the security of supply. As visible in Figure 1.6, there is a constant challenge of matching the demand (black line) and the supply of electricity (stacked colours). The supply variability increases as the share of wind and solar increases, the so so-called variable renewable energy (VRE) have fluctuating productions during the day and throughout the year.

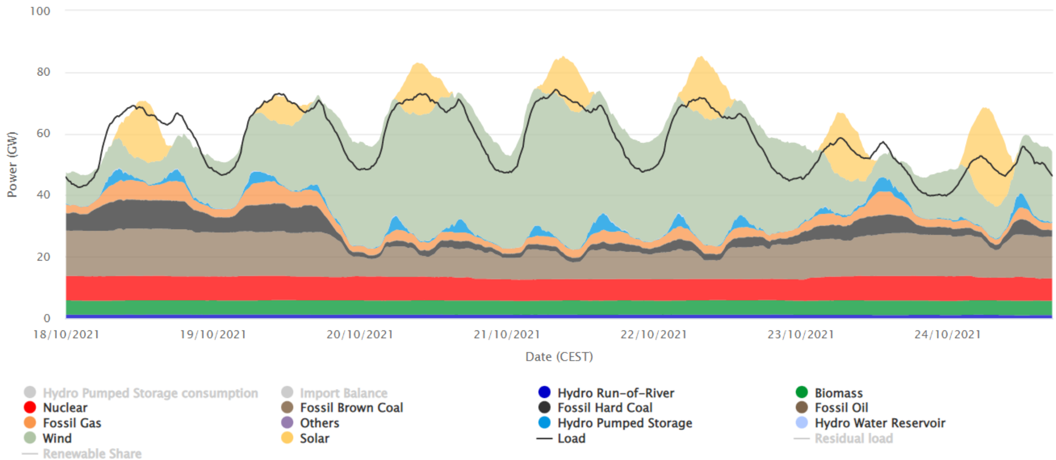

Figure 1.6: German net electricity generation in week 42 of 2021 [Frauhoher ISE, 2021a].

Furthermore, the complexity is increased considering that in 2030 there will be no nuclear power that serves as baseload and no coal or fossil gas that work as dispatchable sources of electricity. Dispatchable electricity power is crucial to ensure the security of supply in highly renewable energy power systems. Therefore, to ensure an equilibrium between supply-demand at all times is necessary to increase power system flexibility via flexible demand, interconnections and storage. In this sense, the German energy transition requires large-scale energy storage to help face the increasing intermittent renewable energy penetration in electricity.

1.4 Storage relevant for the German context

There is a myriad of electrical energy storage (EES) technologies that operate accordingly to different physical principles, hence having different performances and niche applications, as seen in Figure 1.7. Between the electrochemical storage technologies (coloured as light blue), the lead-acid batteries are the most mature technology, having a low cost. However, lead-acid batteries have a diminished life cycle, making them inadequate for energy management. Lithium-ion batteries are commonly deployed in electronic equipment, but several challenges need to be addressed to use this technology at a utility scale, especially the high costs [Taylor et al., 2012].

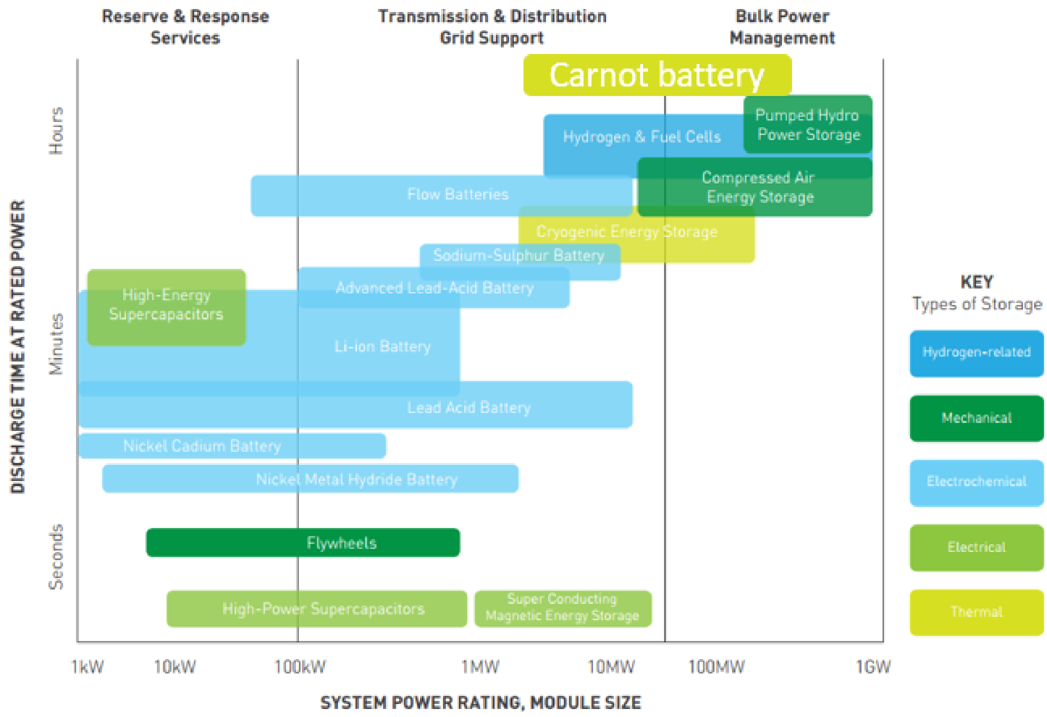

Figure 1.7: Different electrical energy storage and correspondent applications. Own elaboration. Adapted from Michael Geyer, 2019.

The mechanical group includes the most commonly deployed type of EES, the pumped hydro energy storage (PHES). The PHES is limited to favourable geographical conditions, and due to that fact, most of the exploitable locations are depleted [Dumont et al., 2020]. Compressed air energy storage (CAES) is another commercially available option. However, it has the same significant disadvantage as PHES as they depend on geographical conditions. Hence, having limited potential for expansion.

The electrical group includes superconducting magnetic energy storage (SMES) technologies that have a fast response and are suited for grid stabilization.

The hydrogen storage and fuel cells in combination allow seasonal storage that is a great advantage. However, the round-rip efficiency of charge-discharge is low, approximately 30-50%. Moreover, it requires additional energy to compress, store and transport the gas [Cho et al., 2020].

In a future electric German system, with a significant increase of especially solar PV, it is predicted that the residual demand curve will be affected. The duck curve phenomenon requires a shift from daylight hours to the remains. Thus, a grid-scale storage system needs to focus on long-duration storage, approximately 4 to 8h [Dumont et al., 2020].

Despite the significant price drop, it is still expensive to install several modular batteries among the presented options. PHES and CAES present insurmountable geographical barriers, and hydrogen storage has limitations in efficiency, storage and transportation [Cho et al., 2020]. Hence, a window of opportunity is opened for emerging technologies like Carnot batteries to offer alternative electrical storage solutions.

1.5 Carnot battery

A Carnot battery is alternative storage as it stores electrical energy thermally. However, it should always have an electrical input and output as an EES. In order to increase the performance is possible to add thermal energy inputs during the process since the energy is thermally stored and the discharge process is a thermal-power conversion. However, it is important to note that the primary function is to store electricity regardless of possible sub-products such as steam or heat. A configuration that characterizes Carnot possible configuration is visible in Figure 1.8.

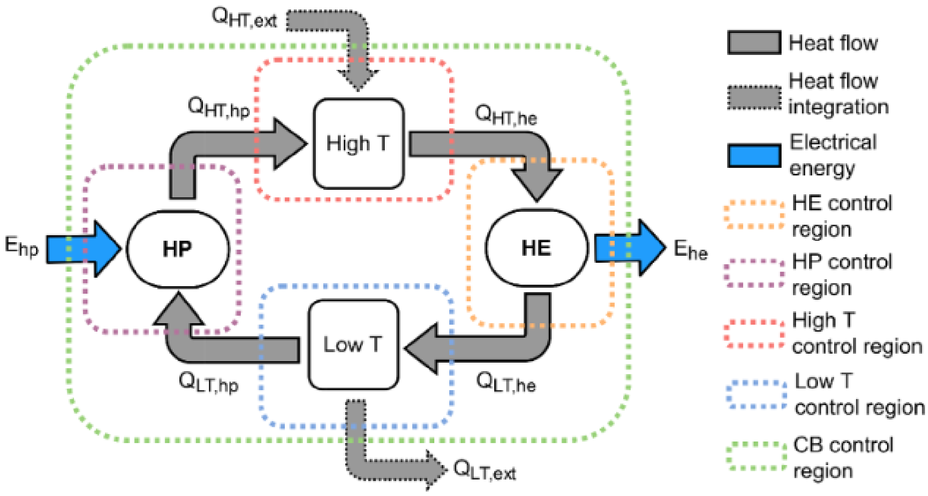

Figure 1.8: Carnot battery concept [Dumont et al., 2020].

In the charging process, electric energy is used to move heat from the low-temperature reservoir to the high temperature one. This is done using a heat pump (HP), resistive heating or others. Hence, this electric energy creates a temperature difference between the low temperature (LT) and high temperature (HT) reservoirs, meaning that electric energy is stored as thermal exergy. The LT and HT reservoirs could be constituted by gas, liquid, solid, changing-phase materials or ambient air. In the discharge process, the thermal exergy allows heat flow from the HT to the LT reservoir, powering a heat engine (HE) that converts it into work. Therefore, the absorbed specific work increases with a more significant temperature difference between the HT and LT reservoirs. The process of converting heat into power is done through thermodynamic cycles, and several technologies can be used to perform this role as heat engines, steam turbines, gas turbines, Organic Rankine cycle machines, and the Lanm-Honigmann process [Dumont et al., 2020].

Consequently, due to all possible technologies that can be used in the three blocks (charging, storage and discharging), the Carnot battery can have several configurations, each with specific particularities.

Among the EES, Carnot batteries have the lowest technology readiness level (TRL), even though they are composed of proven technologies and are becoming more popular [Dumont et al., 2020]. In Germany, Hamburg, a demonstration plant has already been built. The appointed benefits include reducing curtailment, increased supply security, avoidance of grid congestion, and profit from the volatile electricity price. Moreover, Carnot batteries are presented as portable, versatile and scalable solutions [Siemens Gamesa, 2021a].

It is understood that Carnot batteries have a high potential of storing affordably electric energy for hours, a key characteristic considering the significant amount of VRE that is planned for the German power system in 2030. Moreover, the myriad of possible configurations that Carnot batteries have can present a potential for different applications. Given all the mentioned possible advantages and that due to the novelty, there are no studies done of the possible impact of such technology in the German context. Therefore, this dilemma has led to the following problem formulation.

1.6 Problem formulation

What are the applications and the impact of Carnot batteries use to increase renewable energy penetration in electricity by 2030?

In order to properly answer this problem formulation, three underlining research questions have been formulated.

1. What is the maturity associated with the different Carnot batteries configurations?

2. Which applications could contribute to renewable electricity penetration increase?

3. How could Carnot batteries be a technical and economical solution in Germany by 2030?

1.6.1 Delimitation

This subsection describes the scope of this thesis, as the delimitations performed substantially impact the results obtained.

This thesis aims to assess how an emerging solution like the Carnot batteries could help achieve the new German announced goals of achieving an 80% share of renewable energy supply in the power sector. Therefore, focus is defined around the German electricity sector by 2030.

Moreover, Carnot batteries have been restricted to pure electrical energy storage, meaning that no other output such as steam or heat was considered. This factor underestimates the technology but allows a direct comparison with other competitors. Hence, if economic feasibility is proven, the inclusion of other possible applications such as steam or heat would even increase the returns.

Chapter 2

Research Design

The Figure 2.1 shows the contribution of the sections in answering the research question and sub-questions.

As shown, the thesis dilemma is introduced in the Problem Analysis, followed by the problem formulation of the leading research question and three sub-questions coloured as yellow, green, and blue. The corresponding colours are used to portray the relevance of each section to the answer to the sub-questions.

Afterwards, the Theoretical Approach is established by complementing the Carbon lock-in theory with the Multi-level perspective theory. Hence, giving origin to a synergy between these two complementary theories that help to explain how Carnot batteries could evolve from niche technologies to institutionalised ones. The literature review method is used to gather relevant information under defined criteria that are then used as input information for the simulation of Carnot batteries. The energy system analysis comprises the development of three energy pathways for Germany in 2030 and the testing of different storage technologies.

The first research question: *What is the maturity associated with the different Carnot batteries configurations?* is answered in Section 5.1. While the second sub-question *Which applications could contribute to renewable electricity penetration increase?* is clarified in Section 5.2. These pair of RQ has been solved with a comprehensive literature review.

The third RQ: *How could Carnot batteries be a technical and economical solution in Germany by 2030?* is mainly answered in Chapter 6 through an extensive energy system analysis. The results obtain are discussed in the Chapter 7.

Answering these three sub-questions is possible to answer the leading RQ *What are the applications and the impact of Carnot batteries use to increase renewable energy penetration in electricity by 2030?* and obtain a conclusion in Chapter 8. Further considerations are presented in Chapter 9.

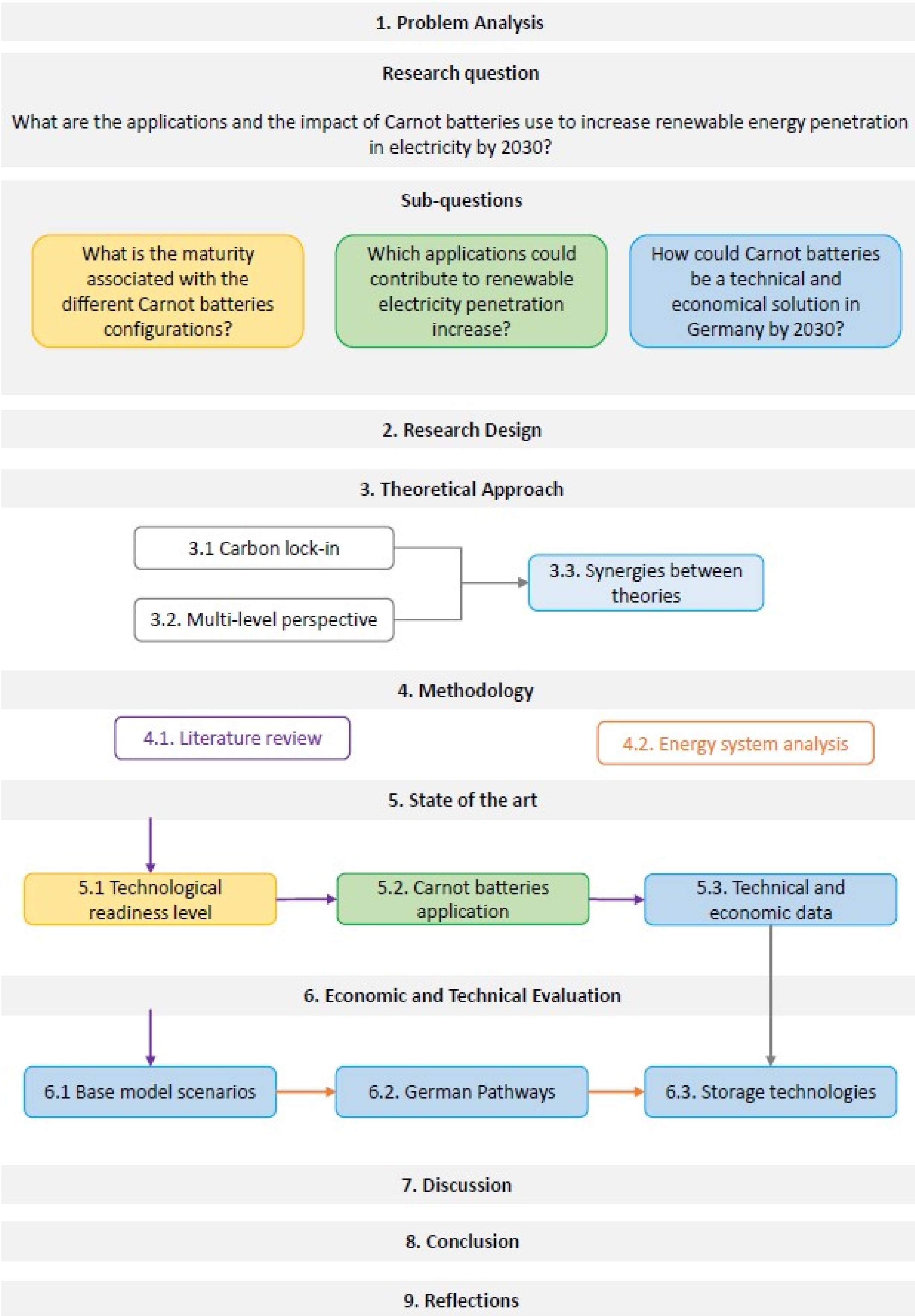

Figure 2.1: Illustration of the Research Design. Own elaboration

Chapter 3

Theoretical Approach

In this Chapter, the theoretical foundation of the thesis is presented. The theoretical approach consists of the research framework and line of thinking. The subsequent approach encompasses carbon lock-in and multi-level prospective theories.

The transition to a clean energy system requires breaking the tendency to reinforce past decisions. As the planning of an alternative renewable energy system is created is necessary to be conscious of the path dependency and how limiting this perpetuating tendency to replicate past decision restricts future alternatives.

The Carbon lock-in concept is an exemplification of how carbon path-depend reliance increases the difficulty to transition to low-carbon technologies. Hence, the carbon lock-in reefers to a specific type of path dependency or lock-in behaviour that is associated to system that emit carbon, negatively affecting a transition to a low-carbon energy system.

3.1 Carbon lock-in

Gregory Unruh first coined the concept of carbon lock-in, arguing that industrial economies are locked into fossil fuels solutions. This lack of apparent future alternatives is derived by a path dependency during the evolution that rejects major changes in the paradigm [Unruh, 2000].

The inertia to new configurations applied in the climate context is defined as carbon lock-in, and it presents a serious barrier in the mitigation of climate change as this emergency requires an immediate shift of the current energy paradigm. The carbon lock-in can be perpetrated by tendentious institutions, by existing technologies and infrastructures, and by behaviours [Seto et al., 2016].

Infrastructural and technological lock-in

The long lifespan of implemented technologies may pose severe challenges to a transition, as the planning of the energy system is performed in a long-term perspective. The lifespan is relevant due to the long time associated with the investment returns, in contrast to the emergent need to replace fossil fuel technologies. A concrete example of this described problem is the considerable sunk costs associated with coal power plants that can lock an investment up to 45 years. Hence, if a country's initial point of energy transition includes coal in the energy mix, the government will have to decide if it disregards the possible profit of fossil technologies or if it compromises the climate goals. In other words, the necessary rapid transition to renewable energies collides with a long-term investment in fossil fuels, thus enforcing a decision between economic returns of past investments and an alternative clean energy system [Seto et al., 2016].

A study has developed an approach to globally assess the carbon lock-in related to different technologies as seen in Figure 3.1. The assessment is based on four dimensions, equipment lifetime, financial barriers to replace with low-carbon alternatives, techno-institutional mechanics, and over-committed emissions [Erickson et al., 2015].

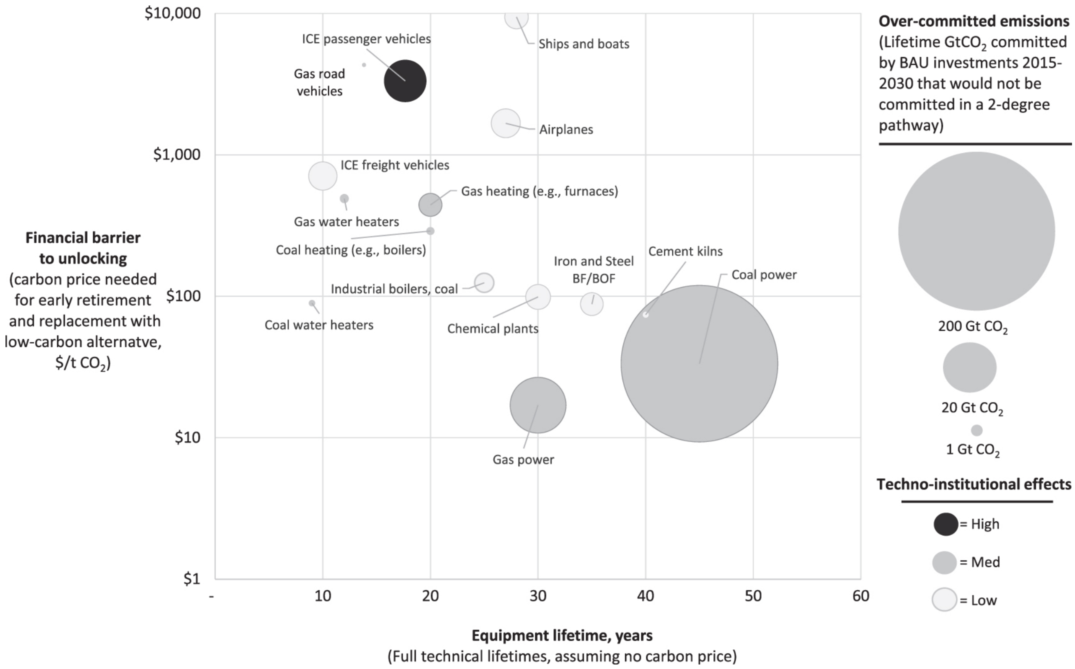

Figure 3.1: Global assessment of carbon lock-in risk technologies [Erickson et al., 2015].

The techno-institutional parameter includes several political and behaviour lock-in hard to quantify. However, a common element is the scale of the technology deployed. The greater the technology use, the largest is the institutional strength of the system that supports that technology. Thus, a darker colour represents a large scale of adoption of one technology and the consequent high carbon path dependency. Concerning the number of technologies deployed, the ICE passenger vehicles are the one that presents a higher techno-institutional challenge.

In addition, the parameter represents in the Y-axis represents the financial barrier to unlock an early replacement of a carbon emitter technology by a low-carbon alternative. It is seen that ships and boats are the technologies that require a higher carbon price since the development of competitive low-carbon alternatives is still diminished.

The over-committed emissions, quantified by the size of the circles, represent the lifetime emissions from 2015 to 2030 of technologies considered in the IEA business-as-usual scenario, compared to the IEA scenario for 2030 that would limit global warming to 2 Celsius degrees. Hence, its a quantitative analysis of the harmful CO_2 emissions emitted globally if the political will does not change. This parameter has indicated that coal-fired power plants present one of the most concerning carbon lock-in risks globally. The elevated risk is related to the amount of planned coal-fired power plants that result in a surplus of 200 Gt CO_2 emissions and a long technology lifetime of 45 years on average [Erickson et al., 2015].

Not only the present technological choices restrain future possibilities, but also all the infrastructure associated. The approach used to plan an urban area such as roads and buildings also promotes a particular behaviour that might be incompatible with clean mobility. Further examples of infrastructure lock-in might encompass the concept of asset specificity, an infrastructure design specifically for one purpose Seto et al., 2016. For instance, natural gas pipeline infrastructures were projected to transport a particular fossil gas, and now it poses limitations to the adaption of the gas infrastructure to renewable gases like hydrogen.

Institutional lock-in

The institutional lock-in differs from the remaining ones as the lock-in aspect is seen as an advantage. The more stable a country is, the more predictable and hence more attractive to investors is. Therefore, institutions typically promote lock-in and naturally benefit those who reinforce the current system. Furthermore, those who benefit from the current status quo gain more power and reinforce the decision actors representing their interests, consequently creating a feedback loop based on institutional lock-in [Seto et al., 2016].

An example is the present difficulty of abolishing government subsidies that support carbon-emitter technologies [Unruh, 2000]. The International Monetary Fund has estimated that global fossil fuel subsidies in 2020 equalled 5.9 trillion USD dollars, equivalent to 6.8 per cent of the global GDP. These excessive subsidies associated with carbon lock-in are predicted to rise to 7.4 per cent of the GDP by 2025 [IMF, 2021].

Behaviour lock-in

The behaviour lock-in is a psychological obstacle that compromises the collective goal of successfully achieving climate goals. There is a crescent lock-in in behaviours as individual citizens feel their actions have little impact and control over such collective problems as global warming, hence also a diminished responsibility to solve it. In this way, individual nefarious behaviours are reinforced, and the collective outcome is globally harmful.

Understanding how behaviour patterns are created is not straightforward. For instance, the new consumption behaviours have increased the energy consumed despite the energy efficiency improvements. In other words, human behaviour is not linear or predictable; what could be a good improvement in energy savings from a new LED technology can be bypassed by an interest in having larger televisions, thus increasing the final electricity utilised.

The abandonment of carbon lock-in requires a deeper understating of the parts involved and the disruptive factors that might promote the desired energy transition.

3.2 Multi-level perspective

The multi-level perspective (MPL) is a theory that explains how established regimes can be modified, provident of the interactions between socio-technical landscape, the socio-technical regime and the technological niches.

Socio-technical regime is an aggregation of different regimes, as seen in Figure 3.2, such as the technological, user and market, socio-cultural, science and policy regime. Hence, it can be described as rules that influence social behaviour. Social-technical (ST) regimes are path-dependent and provide stability, meaning that regimes will not invest in radical innovations and will carry on the existing technology lock-in.

The concept of **socio-technical landscape** encloses broader factors such as collective beliefs and physical infrastructure. These exogenous factors are even more complicated to change than regimes, as the landscape represents collective will.

Niches technologies are novel products that emerge in protected spaces to preserve them from unfair market competition. This protection can be provided by research and development private or public strategies and by subsidies. Niches are also described as a *process of mindful deviation* where it is possible to deviate from the current ST regime. Although the deviation of a current regime is not easily accessible due to its stability, niches are a starting point for transformation. The MPL shows that if some tension is created in the ST landscape or regime, a window of opportunity is opened for niches technologies, as seen in Figure 3.2 [Geels, 2004].

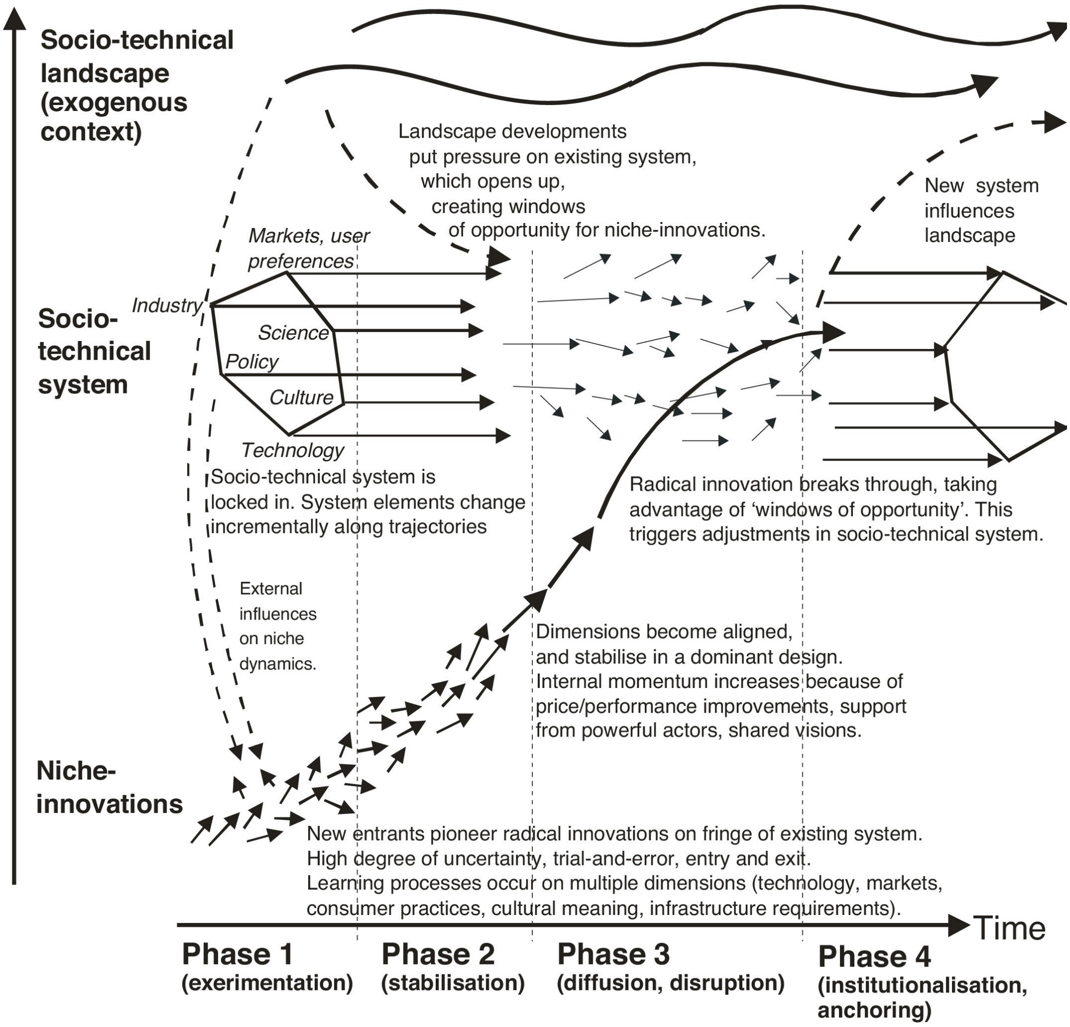

Figure 3.2: Multi-level perspective on technological niches [Geels, 2019].

Therefore, the MPL theory suggests socio-technical changes occur when niche innovations and the landscape alter the regime stability. This destabilization of the path-dependency creates an opportunity for niche technologies to emerge that could successfully be diffused and modify the status quo of the socio-technical system. This socio-technical modification takes several decades to occur and encompass four phases represented in the figure above. The first phase is pictured as experimentation and is characterised by uncertainty and trial-and-error learning. In this phase, niche innovations are assessed in research and development laboratories and testing facilities. If the niche innovation establishes a position in market niches, it will successfully pass to the stabilisation phase. The second phase is characterised by a stabilisation of a *dominant design* that includes standardisation and design guidelines. At this phase, the diffusion of niche technologies starts to increase as the support from stakeholders included in the niche market start to arise. In the third phase, niche innovations find a place in mainstream markets, giving time to the diffusion or disruption phase. This disruption happens when niche technologies manage to take advantage of the *window of opportunity* created by landscape developments. The landscape changes impose pressure on the existing socio-technical system and open opportunities windows. In the fourth and last phase of institutionalisation, the new modifications replaced old paradigms. The niche technologies became again anchored in user preferences, standards, and technical characteristics and are now part of the new stable system.

3.3 Synergies between theories

The carbon lock-in and the multi-level perspective theory are complementary, and it is believed that a synergy between both theories helps to understand the reasons behind stable regime and the approaches to alter and disturb that stability to create the needed changes.

The carbon lock-in theory explains which mechanism reinforce lock-in in the different types, behaviour, institutional or technological lock-in. The carbon lock-in theory states that some existing mechanics increase the stability of the system, this view is is compatible with the socio-technical system vision of dynamically stability.

As shown in the Figure 3.3, the ST regime is *dynamically stable*, reinforced by path dependency and carbon lock-in technologies, behaviours and institutions.

It can be understood that technology and infrastructure lock-in, explained in the Carbon lock-in theory, are compatible with the idea of regime stability, in particular with the technological and industrial dimensions. Afterwards, industry's sunk costs and other technologies' areas promote a technological lock-in. Furthermore, the behaviour lock-in can be understood as both individual and collective. The user preferences, culture and social practices such as science could be reconcilable with the particular aspect of persisting with the same manner of thinking, both individually collectively. Finally, the policy parameter in the ST regime can be compared to the institutional lock-in stated in the carbon lock-in theory. To an extent, the markets could also be included as institutional lock-in as markets are political constructions.

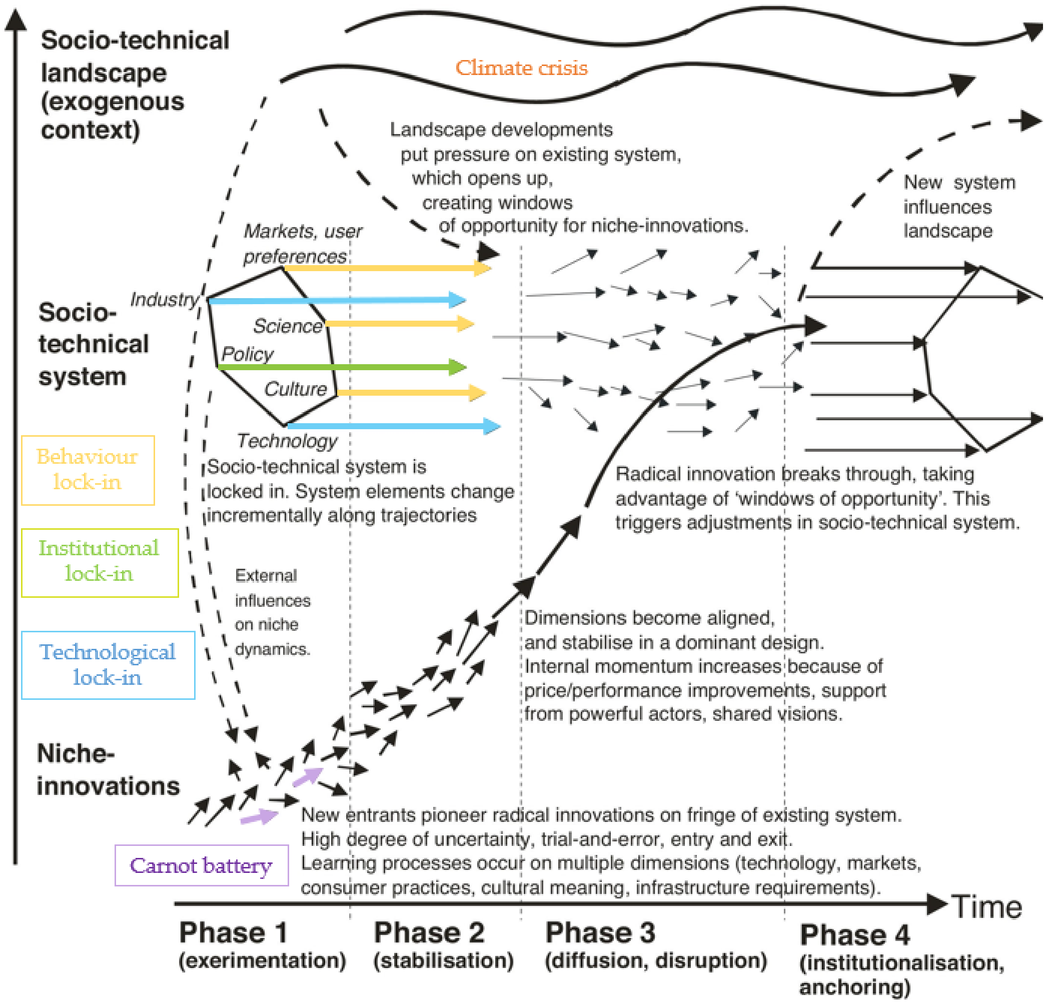

Figure 3.3: Synergies between Carbon lock-in and Multi-level prespective theory. Own elaboration. Based on Geels, 2019 and Seto et al., 2016.

The MLP approach has shown that a niche technology such as Carnot batteries could disrupt the socio-technological system and break the carbon lock-in present in the energy system. This way, the landscape ambition to fulfil the Paris agreement could be one more step close to being fulfilled.

Therefore, this thesis will test the feasibility of the institutionalisation of Carnot batteries by 2030, bearing in mind that to succeed, it has to find one or more mainstream markets and prove its economic and technical feasibility. The only parameter that will be analysed of the regime will be technological, meaning that this study will disregard the existing constraints in the industry, policy, culture, or markets.

Chapter 4

Methodology

In this chapter is presented the methods used in the project, namely the methodology utilised in the literature review and energy system analysis.

4.1 Literature review

In pursuance of finding relevant information, several resources were used, such as technical reports, articles and institutional reports. The literature review was crucial in finding a relevant research problem, and then it was used as a method to obtain valid information about theories and the state of the art of Carnot batteries.

Considering Carnot batteries are still a niche technology and encompass an overarching definition, several terms can be used to refer to Carnot batteries. Some of the related terms used to perform a literature review were:

- Electric Thermal Energy Storage (ETES)
- Thermoelectric Energy Storage (TEES)
- Pumped Thermal Electricity Storage (PTES)
- Pumped Heat Electricity Storage (PHES)
- Liquid Air Energy Storage (LAES)

Another aspect related to the novelty of the Carnot battery technological concept is the limited information available. Therefore, it is essential to define criteria of validation that ensure an reliable reflection of the technology.

Sources validation

The reliability of the information was prioritised by primarily collecting only information from scientific articles. This approach accredits confidence in the information collected as the articles have to be submitted to a peer-review process.

When relevant information could not be found in scientific articles, other sources of information, such as relevant reports from recognised institutions have been prioritised. Nevertheless, due to the novelty aspect of Carnot batteries, it was exceptionally challenging to find relevant information and one Wikipedia page was also used to collect information. This rather dubious source of information was found to be reliable since it was written in the scope of the IEA Energy Storage *Task 36 Carnot batteries* [IEA, 2021 and Wikipedia, 2021].

The other criteria used in data collection was the date of publication, giving priority to the most recent published information. In this study, both primary and secondary sources were utilised. Taking into account that ideally, primary sources are more reliable sources of information.

4.1.1 Primary sources

A primary search is described as the information collected directly from the source. The most significant primary source utilised to gather information regarding Carnot batteries was the Siemens Gamesa, 2021a. This source of information was prioritised since it supplied a recent primary source applicable to the German case study, as the data collected were from a testing platform located in Hamburg. Data were also directly collected from the Tesla website (Tesla, 2022) concerning competing electrical storage technologies.

4.1.2 Secondary sources

Secondary sources include information gather through second-hand sources such as websites, online libraries, databases, and online newspapers. Hence, secondary sources imply an analysis of a primary source.

The article *Carnot battery technology: A state-of-the-art review* [Dumont et al., 2020] was used as the principal source of information regarding the state of the art of Carnot batteries and technical and economic data. Moreover, the Danish Energy Agency database (Danish Energy Agency, 2020) was also used to obtain electrical storage technological costs and performance for 2030.

The information collected was then added to the Bibliography section in accordance with the type of source. The information gathered was both from primary and secondary sources.

4.2 Energy system analysis

In the energy system analysis, one can follow two archetypes of modelling approaches: optimisation and simulation. In the optimisation model, the system design is determined by the optimisation procedure. Hence, this approach assumes that there is an optimal solution concerning a number of factors. The downside of this approach is that the optimisation software makes the analytical decisions, making it harder to be conscious of the decision process and consequent impacts. On the other hand, the simulation approach allows the user to define several scenarios and compare the outcomes accordingly to several parameters. In other words, the optimisation model obtains the best solution while the simulations test several solutions. Since this thesis aims to evaluate the economic and technical feasibility of the Carnot batteries, it was understood that the simulation of scenarios that test different Carnot roles and compare the evaluated technology with a direct competitor is the most suitable approach to obtain the wanted answers [Lund et al., 2017]. Therefore, the analytical approach that will be followed is represented in Figure 4.1.

Figure 4.1: Analytical approach through simulation. Own elaboration. Based on Lund et al., 2017.

The fight against climate change calls for a unified and effective carbon emission reduction across all sectors. Therefore, the energy planning towards a carbon-neutral system must include the individual sectoral challenges but also the possible synergies between sectors. Acknowledging a symbiotic behaviour across the energy sectors and infrastructure is especially relevant when flexibility and storage are considered. Hence, the simulation tool should account for cross-sectoral integration and allow a high resolution in time due to the significant fluctuation of renewable energy sources.

Considering all the above EnergyPLAN is a suitable simulation tool as it allows an hourly analysis and cross-sectoral integration approach of an energy system, crucial for analysing fluctuating energy sources such as VRE [Connolly et al., 2010].

EnergyPLAN

The EnergyPLAN is a simulation tool that has a deterministic process with no stochastic elements. The developers characterised this method as *analytical programming* since it evaluates user-defined energy systems rather than calculating an optimised solution [Lund et al., 2021]. The parameters inserted and the outcomes assessed are seen in Figure 4.2.

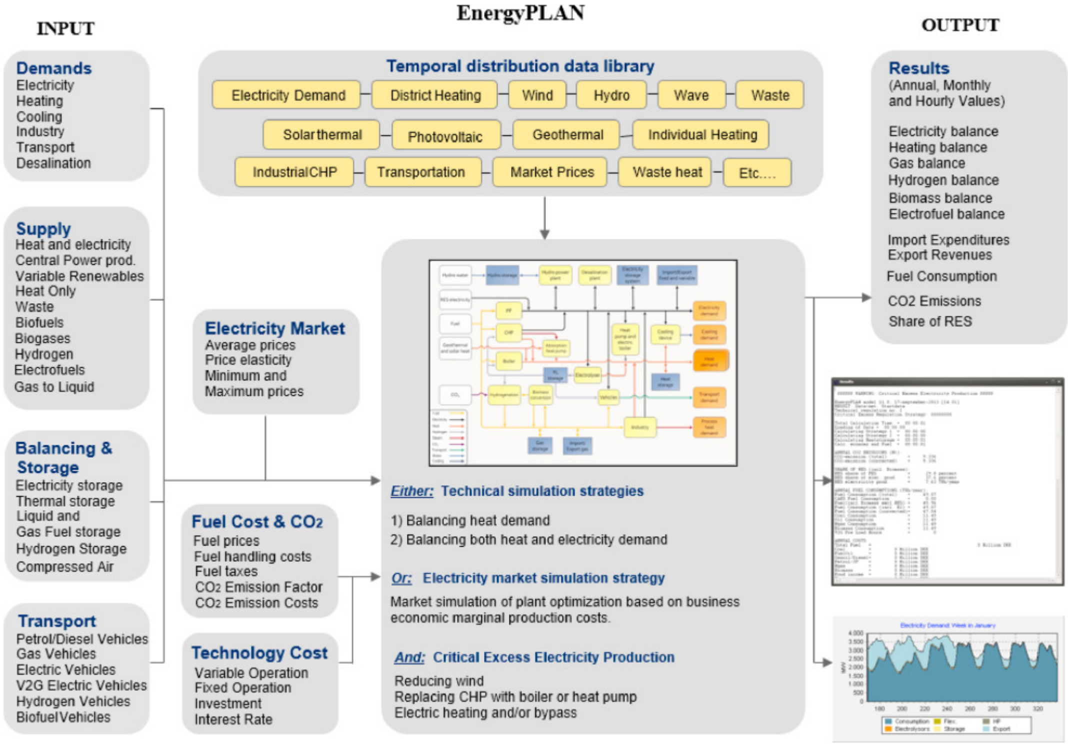

Figure 4.2: EnergyPLAN inputs and outputs [Lund et al., 2021].

In the view of allowing several options to the user-defined energy system, the tool considers two simulation strategies, one technical that analyses the best hourly energy balance that consumes less fuel, and a second market-economic strategy that evaluates the best economical solution considering the electricity market. Since the market-economic strategy focuses on the electricity market bids, it only analyses a short-therm window that considers solely variable costs. This is the current market approach developed to achieve the best economical solution with dispatchable technologies. However, the transition towards a renewable energy system adds non-dispatchable technologies that require the redesign of the market to consider the long-term costs of producing renewable electricity [Lund et al., 2021]. For that reason, it has been chosen a technical strategy.

The graphical representation of the steps carried out in the technical simulation strategy is visible in Figure 4.3.

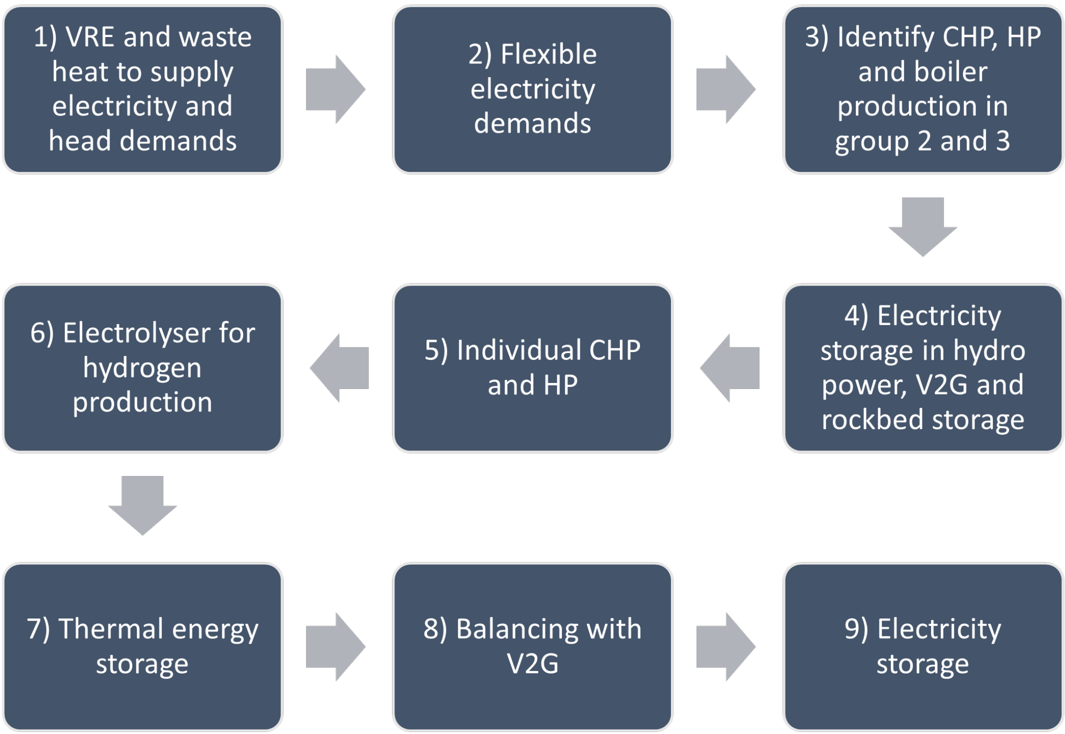

Figure 4.3: Steps carried out in the technical simulation strategy. Own elaboration. Based on Lund et al., 2021.

Notes: VRE = Variable renewable energy; CHP = Combined heat and power; HP= Heat pump; V2G = Vehicle to grid.

The technical simulation strategy is composed of the nine steps described in the boxes, plus a recurrent step represented by the arrows. This recurrent step summarizes the electricity demand and applies a number of regulation strategies to reduce critical excess electricity production (CEEP) accordingly to the prioritization chosen by the user. The regulation strategies include the reduction of renewable electricity production, the replacement of CHP production with fuel-based boilers, the substitution of fuel-based boilers with electric heating, increased CO_2 hydrogenation and the part-loading of nuclear power.

In conclusion, the EnergyPLAN has a holistic approach to the energy system. Hence it can analyse the impact of the electrification of sectors like transportation, heating, and industry would have on the power sector. This factor is especially crucial as the main contribution tested of the Carnot technology will be the balancing of the power sector.

4.2.1 Energy system pathways

This subsection presents the methods utilised to obtain the energy system pathways for the year 2030. The different pathways will be used to evaluate the impact of electricity storage technologies, such as lithium-ion and the Carnot battery.

Taking into account that the main focus of this thesis is not to model the German energy system in 2030, but to evaluate the impact of Carnot batteries, it has been decided to use as benchmark already built scenarios. Therefore, it has been chosen to use the scenarios developed in the Heat Roadmap Europe (HRE). The HRE study has analysed and simulated 14 countries, including Germany, to study the impact of different energy strategies [Paardekooper et al., 2018].

In the HRE study, the input data for EnergyPLAN was obtained from different models such as FORECAST, Peta4, and JRC EU-TIMES. Afterwards, the outputs obtained in the EnergyPLAN were used to build the heat roadmaps.

There is a drawback of using already built scenarios since the mentioned scenarios were built using an old version of EnergyPLAN. Therefore, the results are not the same by running the scenarios in the most recent version 16, which contains several modifications and expansions. One visible aspect of this occurred when the BL 2050 scenario was run, and it was necessary to add 3 MW of CHP installed capacity to the already built scenario to avoid critical import needed. This warning message means that electricity production is insufficient to meet the demand. This situation could be solved by increasing transmission line capacity (not applicable to this scenario since it is done in island mode) or increasing the electricity production such as the CHP installed capacity (chosen option).

Transmission line

Another characteristic that impact the outputs obtained is that all scenarios are simulated in *island mode*, meaning no transmission line capacity between Germany and neighbouring countries are considered. No information was found why no transmission line capacity was considered. It can be supposed that the main reason was to test how heat pumps used in District heating would behave without the external electricity market. In other words, how the heat would be supplied accordingly to VRE availability. Another reason could be that the simulation of external electricity markets is brutal to be precise, even harder for a country like Germany that has four different TSOs and exchanges electricity with eleven countries [Frauhoher ISE, 2022].

A further condition of relying upon the transmission line is that it is assumed that the external market would have available excess production or available stored electricity at the moment needed. This uncertainty increases when considering a future European energy system based on renewable energy, intermittent, geographically dependent resources. For instance, if Germany would have to import electricity because the wind energy production was low, the most common would be to import from a nearby country, which presents lower transmission costs but would most likely also have low wind resources available. Therefore, countries with abundant storage, such as pumped hydro, serve as 'external batteries' that profit from the electricity price fluctuation. However, this willingness to serve as external batteries for other countries is likely to decrease, as the hydro reservoirs have limited expansion capacities and the need to use the available storage to regulate and decrease the cost of electricity nationally increases with the inclusion of higher shares of renewables.

Thus, no transmission line capacity will be considered in the created pathways. This method was some disadvantages as it could mean that some installed capacity is over-dimensioned since a connection to an external electricity market would ensure additional flexibility. Throughout the transmission line it would be imported electricity in hours when production is lower than the demand. When the same unbalance of production and demand occurs in island mode, the solution is to use other internal flexibility options and increase production capacity. Therefore, this method presents the ideal case for storage that can store electricity, such as the Carnot battery.

Linear regression

In the HRE study, it has been developed four main scenarios for each country [Paardekooper et al., 2018]. However, only three of the scenarios explained below will be utilized to obtain an intermediate scenario for 2030. The fourth scenario that has been neglected is the heat roadmap scenario, as this scenario evaluates the feasibility of district heating and optimal heating system, factors out of the scope of this thesis.

The HRE has developed two baseline scenarios, one for 2015 (**BL 2015**) and another for the year 2050 (**BL 2050**), that are used to represent a business-as-usual (BAU) progression. The evolution from 2015 to the 2050 baseline scenario involves the measures stated in the Clean Energy Package, as in 2018. An example of an stated measure is the German nuclear phase-out by 2022.

The other scenario seen as pertinent is the Conventionally Decarbonised (**CD 2050**), which illustrates a scenario that aims for higher decarbonisation than the 2050 baseline. These HRE scenarios are scrutinised in Section 6.1.

Both 2030 pathways are obtained using a linear regression between the corresponding 2050 scenarios (BL and CD 2050), and the 2015 baseline (BL 2015), as seen in Figure 4.4.

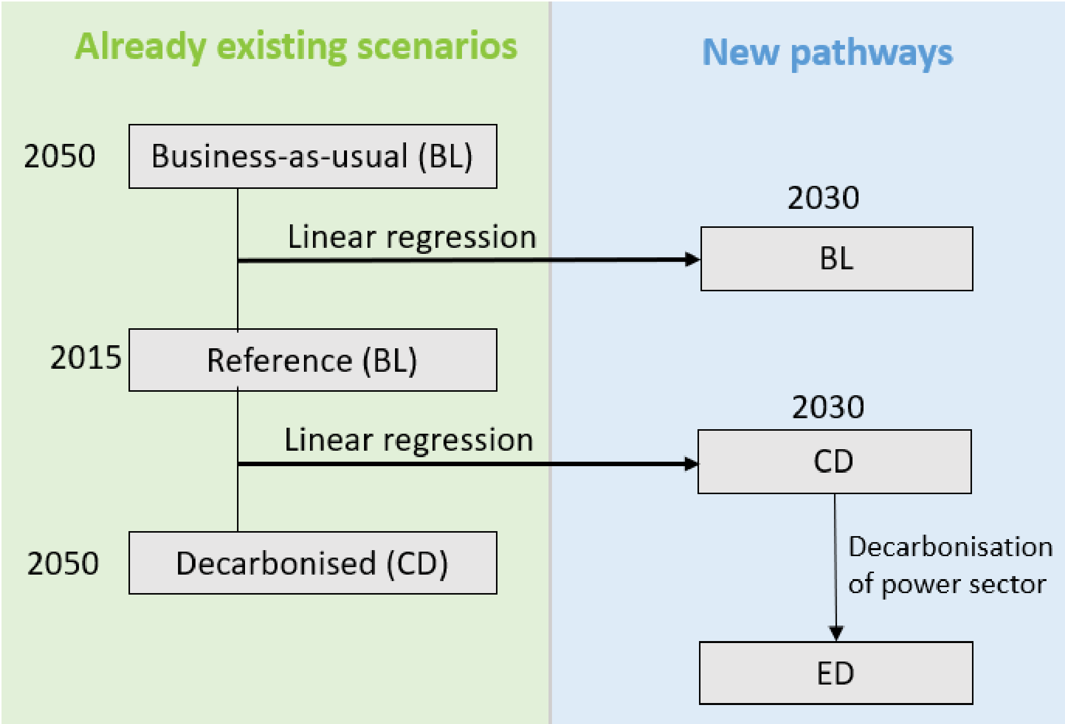

Figure 4.4: Method to obtain the three different pathways. Own elaboration.
Notes: BL = Baseline; CD = Conventionally decarbonised; ED = Enhanced decarbonisation.

The benefit of utilising a baseline pathway for the year 2030 is firstly to have a reference for comparison of no further action, which means that throughout the comparison with a BL pathway is possible to quantify the costs and advantages of additional measures to decarbonise the energy system.

The CD pathway represents a decarbonisation aligned with the new government coalition goals, and the EH pathway portrays the total decarbonisation of the power sector. Nonetheless, the remaining sectors are identical for the EH and the CD pathway. Hence, it is possible to quantify the cost of total decarbonisation of the power sector in Germany and how different solutions could contribute to the increase of VRE share.

Primary energy supply

The overview of the sectors such as power, heating, cooling, industry and transportation of the three pathways are detailed in the Appendix A.

The distribution of the primary energy supply in the three pathways is represented in Table 4.1. The PES considered depends on the political context in each pathway and the corresponded phase-out ambitions of fossil fuels.

Table 4.1: Primary energy supply in the three different pathways and its political context. Own elaboration.

Sector	BL	CD	ED
Power	Coal Oil NG Biomass VRE	NG Biomass VRE	Biomass VRE
Heating and Cooling	Coal Oil NG Biomass	Oil NG Biomass	Oil NG Biomass
Industry	Coal Oil NG Biomass	Oil NG Biomass Hydrogen	Oil NG Biomass Hydrogen
Transport	Oil NG Biofuel	Oil NG Hydrogen Biofuel	Oil NG Hydrogen Biofuel
Political context	Goals before coalition	Goals after coalition	Enhanced decarbonisation
Phase-out	Nuclear in 2022	Coal in 2030	No NG in the power sector

As represented above, nuclear energy will not be contemplated in any 2030 pathway since by the end of 2022 Germany will achieve its goal to fully phase-out nuclear power plants. In the baseline scenario, coal has a role as a primary energy supply since before its recent ambition to anticipate the coal phase-out, the German target year of coal phase-out was in 2038. On the other hand, in the CD pathway, the Coal phase-out ambition is aimed for 2030, aligned with the new government coalition, meaning that no coal has been considered in the pathway. The ED pathway represents the total decarbonisation of the power sector. Hence, natural gas is not considered an energy source in the power sector, but it still accounts for the remaining sectors. On this ground, the ED pathway represents a more ambitious political context related to the CD.

The installed capacity in the power sector for the BL and CD pathway was obtained through linear regression. The values derived are represented in Table 4.2.

Table 4.2: Renewable energy installed capacity per pathway. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**	**Enhanced (2030)**
Wind onshore (MW)	27202	50644	195000	37248	99115	***100000***
Wind offshore (MW)	139	20732	104000	8965	44651	***70000***
Solar PV (MW)	17093	78055	275000	43219	127625	***200000***
River hydro (MW)	2977	2977	3402	2977	3159	3159
Tidal (MW)	0	0	216	0	93	93

The values in the EH pathway highlighted and in italic had to be modified in other to obtain a total decarbonised power sector. The power sector is supplied by 367 TWh/year of natural gas in the CD pathway. However, natural gas is not accounted for in the Enhanced Decarbonised scenario. Therefore, if no changes are made in the supply, the EnergyPLAN would automatically assume that primary energy once supplied by NG would be supplied by biomass. This automatic process occurs as no maximum amount of biomass is established in EnergyPLAN. Nevertheless, there is a concern about the amount of biomass available, so the maximum biomass supply will be assumed to be 1200 TWh/year, the same value in the HRE scenario. Thus, it ensures a feasible amount of biomass is consumed.

Therefore, it is necessary to increase renewable energy production to maintain biomass consumption below the maximum level. The impact assessment of increasing onshore wind, onshore wind, and solar production is visible in Figure 4.5.

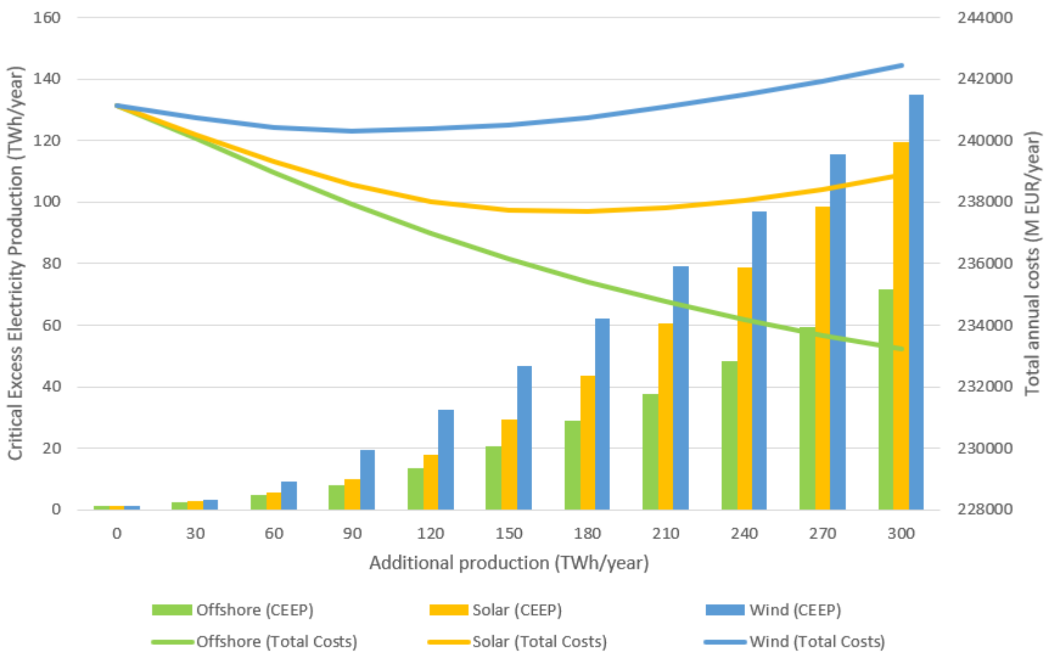

Figure 4.5: Assessment of VRE production increase. Own elaboration.

The figure above represents the Critical excess electricity production on the left axis. The lower the CEEP, the more compatible is the production in relation to the energy system. Concerning this parameter, the wind offshore is the power production that is the best option concerning the ED pathway. The total annual costs represented in the right axis show the economic feasibility of the additional renewable production. These costs decline compared to the initial cost, as affordable VRE replaces the costly biomass use. Likewise, the wind offshore is the one that presents the best performance in this parameter.

Consequently, it was first added wind onshore, up to 70 GW, as this value corresponds to the German ambition in 2045. This addition alone was insufficient to reduce the biomass supply to near 1200 TWh/year, so 200 GW of Solar PV and 100 GW of wind onshore were also added. These two values of solar and wind onshore correspond to the goals proposed for the year 2030 in the recent government coalition [Koalitionsvertrag Zwischen, 2021].

4.2.2 Modeling of Carnot batteries

There are several options to simulate Carnot batteries in the EnergyPLAN. The first one is as high-temperature rock-bed storage. The high-temperature storage can be simulated to charge only in case of critical excess electricity production or to balance all electricity export and import. Additionally, when high-temperature storage is connected to CHP plants, it allows the storage of excess electricity as steam that can be used in CHP. Hence, the use of storage can also reduce fuel consumption.

The other option is to simulate the Carnot as a block, where there is an input and output of electricity, hence simplifying the Carnot technology as electrical storage. Considering that this study intends to analyse the impact of Carnot in the power sector, it is understood that simplification and neglect of the possible extraction of heat is not a limitation. This approach also directly compares the Carnot with electrical storage technologies competitors. The following parameters are required as input in the EnergyPLAN.

EnergyPLAN parameters

The electrical storage in the EnergyPLAN is characterised by:

- Charge electric capacity (MW)
- Charge efficiency (%)
- Discharge steam capacity (MW)
- Discharge efficiency (%)

- Storage capacity (GWh)

Moreover, to obtain the total investment costs (M EUR) and the annual costs (M EUR/year) associated with the inclusion of Carnot batteries is necessary to insert the cost of million euros per GWh, the lifetime in years and the percentage of investment associated to the operation and maintenance.

MATLAB

It was used the MATLAB Toolbox described in detail by Cabrera et al., 2020. This specific tool was adapted to vary the installed charging, discharging and storage capacity. This tool was chosen as the best approach to obtain the least costly pathway for the inclusion of the different storage technologies (i.e. Carnot and electrical storage competitors) as it allows the iteration of several scenarios. Hence, improving the level of detail and certainty of the analysis.

The code was adapted to follow two different approaches using the MATLAB Toolbox. The first one is the most simple, which assumes an initial charging, discharging, and storage capacity based on a real example and increases the installed capacity maintaining a proportional ratio between all the inputs. In other words, the total storage capacity is increased simply by adding more storage. This approach is used in the two lithium grid-scale storage technologies since the capacity can not be increased without increasing the overall amount of batteries in this kind of electrical storage. The same does not happen in vanadium batteries and the concrete case of Carnot batteries.

The second approach tested also assumes an initial starting point based on a real example but considers that the storage capacity can be increased without increasing the charging and discharging power. In this approach the code runs the optional combination between energy and power stored for a given pathway. This approach was understood as relevant in the Carnot case as it is assumed that the energy stored can be increased by increasing the dimension of the thermal energy storage.

4.2.3 Sensitivity analysis

A sensitivity analysis of the addition of the transmission line has been performed to assess the implications of the pathway modelling in island mode.

In relation to the interconnection costs, the same values were assumed as the one used in the IDA 2030 vision. Specifically, 1.2 million euros per MW, a lifespan of 40 years, and an operation and maintenance cost equalled 1% of the investment. Moreover, was not included any distribution that would establish the import and export hourly distribution. Thus, the transmission line will be used according to the needs. This assumption, as explained above, presents severe limitations as it is assumed that on the other side of the transmission always exists available demand and production, to be imported/exported accordingly to the country's electricity balance. Despite this limitation, it was still relevant to test the impact of considering an external electricity market as, in reality, the electrical batteries would have to compete directly. The external electricity price followed the Nord Poll system of 2013 and had a resulting average price of 51 EUR/MWh, anew to the method used in the IDA 2030 vision.

A maximum transmission line capacity was first assumed to obtain the maximum possible imports or exports in the given pathway. For instance, the maximum capacity used in one hour for the ED pathway was 125513 MW. Hence, this value will be defined as the maximum value in the range of possible transmission line capacity.

Chapter 5

State of the art

In this Chapter, the state of the art of Carnot battery technology is presented, encompassing the technological readiness levels of different configurations, projects already developed, applications in the power sector and economic and technological information.

In the Problem Analysis (Subsection 1.5) it was presented the Carnot battery definition and its versatility. In order to evaluate the state of the art is crucial to evidently define all possible configurations under the umbrella of Carnot batteries. Therefore, the possible configurations are simplified in Table 5.1.

Table 5.1: Carnot battery possible configurations. Own elaboration. Based on Dumont et al., 2020.

Charging	Storage	Discharging
Electrical heater	Sensible	Rankine cycle
Heat pump	Latent	Brayton cycle
Other	Thermochimical	Other

The charging part, also mentioned as electricity to heat, can be performed using technologies such as an electrical heater, heat pumps both reverse Rankine cycle and reverse Brayton cycle, and others such as the Claude cycle or Lamm-Hogimann process. The thermal energy storage most common materials used in Carnot batteries are hot water, molten salt, rocks, and liquid air [Wikipedia, 2021]. In the discharging or heat to power process, heat is converted by thermodynamic cycles as the Rankine, Brayton, or Lamm-Honigmann process [Dumont et al., 2020].

In the interest of evaluating the maturity of Carnot batteries, Dumont et al., 2020 has grouped the different Carnot configurations into five distinct groups.

5.1 Technological readiness level

The four groups and the correspondent, technological readiness level (TRL), the expected range of power and capacity, efficiency and cost are represented in the

Table 5.2.

Table 5.2: Comparison of different Carnot batteries groups. Own elaboration. Based on Dumont et al., 2020.

Group	TRL	Power (MW)	Capacity (MWh)	Efficiency (%)	Cost ($/kWh)
EH and Rankine	9	10 to 100	100 to 2,000	12 to 55	94
Liquid air	9	10 to 7,800	50 to 650	12 to 60	66 to 666
HP and Rankine	7	up to 10	up to 40	30 to 73	68 to 117
Brayton	5	up to 100	up to 400	60 to 70	55 to 198
Lammm-Honigmann	1	N/A	N/A	4 to N/A	N/A

The TRL is a scale that evaluates the maturity of one technology from 1 up to 9. Where the first level represents only an identification of the concept and possible applications, the ninth level depicts a proven system ready for commercialisation. At level seven, a pre-commercial technology is demonstrated in a real environment [Innovationsfonden, 2017]. Between the myriad of maturity levels observed in the different Carnot groups, as seen in Table 5.2, it has been assumed that only an equal or higher level 7 could guarantee that the Carnot battery would be a commercially available technology by 2030.

To assess the applications of each Carnot group, one real example for the EH and Rankine, liquid air, and HP and Rankine groups will be presented.

Electric heating and Rankine Cycle

Siemens Gamesa has already developed two prototypes in Hamburg, one in 2014 and another in 2019. Both prototypes have the same roundtrip efficiency of 45%, but the most recent has increased the electrical power to 1400 kW and capacity of 12000 kWh. This kind of Carnot battery utilises restive heating and air as heat transfer fluid. The heat storage in volcanic rocks can reach 600 Celsius degrees.

The power cycle is composed of a steam turbine that allows the conversion of steam into electricity. Other possible outputs from the Siemens ETES are the use of process steam for industrial processes and water for district heating or cooling. This solution is already commercially available [Siemens Gamesa, 2021a].

Liquid air

In 2011 a liquid air prototype was developed by Highview Power in the United Kingdom. The process involves cryogenic energy storage (liquefied air at -196C) and cold and hot thermal storage. The only output in this process is electricity [Highview Power, 2022]. This prototype has a power equivalent to 300 KW, a capacity of 2.5 MWh and a round-trip efficiency of 8%, but the projections for a full-scale facility are 50% [Dumont et al., 2020]. The concept is already commercially available with a worksite in Carrington to enter in operation by 2023 Highview Power, 2022.

Heat pump and Rankine

Compressed Heat Energy Storage (CHEST) has given origin to the CHESTER project. This project combines high-temperature thermal energy storage and Organic Rankine cycle units, and merges the power and heat sector. The efficiency can be increased with the integration of waste heat; such thermal improvement can generate efficiencies between 70 to 150 per cent [CHESTER, 2022].

5.2 Carnot batteries applications

Taking into account the projects describe previously, the synergies between all sectors and the possible applications of the Carnot battery included in a smart energy system is represented in Figure 5.1.

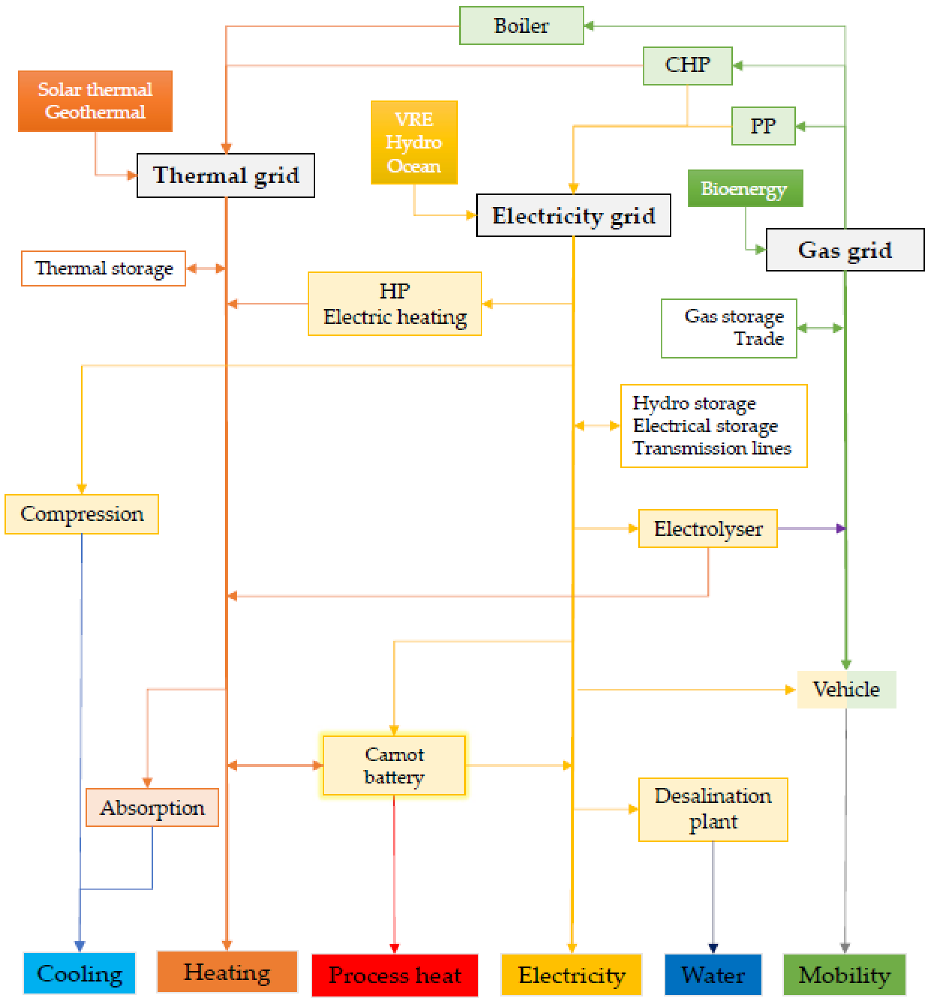

Figure 5.1: Carnot battery applications and impact in the smart energy system. Own elaboration.

The image above represents all possible outputs from a Carnot battery, such as heat, process heat, and electricity. However, the scope of this study limits the Carnot contribution as a flexibility provider in the electricity sector.

5.2.1 Grid-scale energy storage

Carnot batteries have no geographical constraints, such as CAES, as the storage is done in affordable, sustainable materials [McTigue, 2019]. Since Carnot batteries are designed for large storage capacities and are geographically independent, this technology could be viable for grid-scale energy storage. Some of the benefits of using Carnot as grid-scale storage could include the curtailment reduction of VRE and the consequent profit from the fluctuating price of electricity. Moreover, they could work as virtual power lines, meaning that when placed in congested locations, the balancing service provided could avoid costly grid reinforcements. Therefore, Carnot batteries are seen as a technically feasible option that can help to avoid grid congestion and transmission lines reinforcements [Siemens Gamesa, 2021a].

Carnot batteries' economic feasibility as grid-scale energy storage depends on the market competitor. Currently, the technology seen as prominent is Lithium-ion batteries.

Grid-scale electrical storage competitors

In the interest of comparing Carnot's economic feasibility with other utility-scale batteries, two lithium-ion models were found relevant. The first one being a Samsung SDI E3-R135 since all details costs can be found in the Danish Energy Agency database [Danish Energy Agency, 2020]. This database is seen as a reliable source of information and contains price projections for 2030. The other pertinent battery identified was the Tesla Megapack. Similarly to Samsung, it consists of several modules connected in a container size module that allows mobile and independent geographical balancing services [Tesla, 2022].

5.2.2 Retrofit of coal-fired power plants

The retrofit of coal-fired power plants into Carnot batteries and evaluated for the Chile context. As seen in Figure 1.5, this study has proposed to integrate high-temperature molten salt storage into a phase-out coal power plant. Therefore, reusing the current Rankine steam cycle and replacing what once was supplied by coal with a Carnot battery [GIZ, 2020].

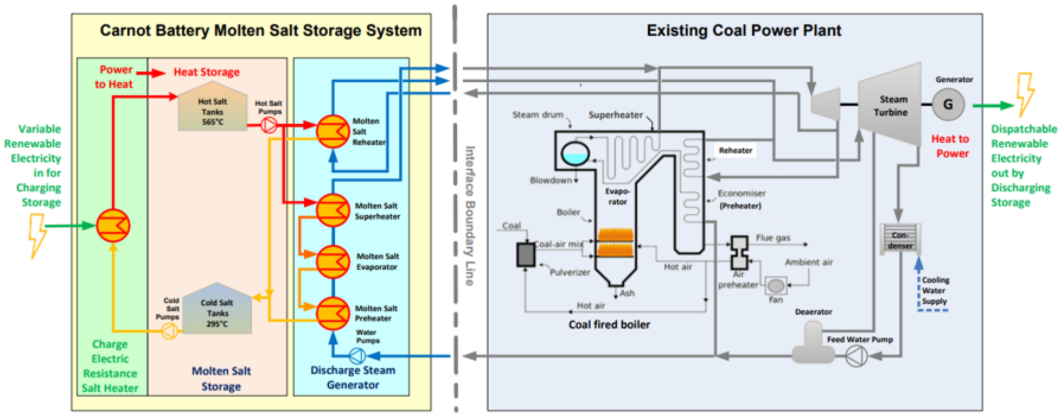

Figure 5.2: Retrofitting of a coal power plant with Carnot battery [GIZ, 2020].

This Carnot battery concept comprises an electrical heater, molten salt storage, and a steam generator. The combination of a molten salt storage and molten salt steam generator is a tested solution deployed in concentrated solar plants. This study concludes that is technical possible to convert coal, gas and biomass thermal power plants into Carnot batteries [GIZ, 2020].

Another project, the Coordinated Operation of Integrated Energy Systems (CORE), has tested several Carnot batteries configurations, and it has arrived at it appears to be a ratio of costs between the charging and discharging parts, visible in Figure 5.3.

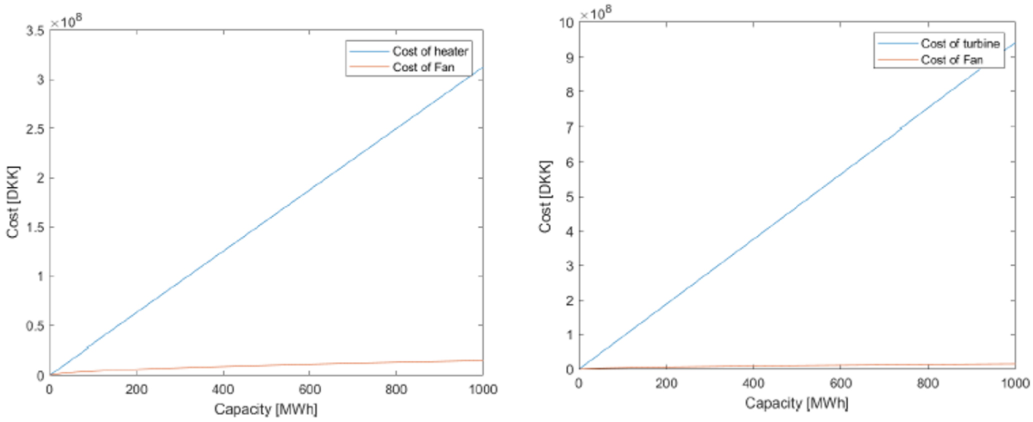

Figure 5.3: Cost of charging (left) and discharging (right) of a high-temperature rock-bed [Sorknaes et al., 2020].

This ratio of discharging being three times more expensive than charging will be used to base the assumption costs in the following section. Furthermore, the CORE study showed a promising role for Carnot batteries when connected to CHP in the Danish 2050 context—keeping in mind a significant uncertainty level due to the configuration's novelty [Sorknaes et al., 2020].

German context

In 2020, 37% of German electricity was obtained via steam turbine from coal and nuclear, and 12% from gas turbine supplied by natural gas [Frauhoher ISE, 2021a]. Hence, half of the German electricity is generated via thermal-power conversion that will soon be decommissioned. These installations have vital high voltage power connections and operational technologies with no planned use, as represented in Figure 5.4.

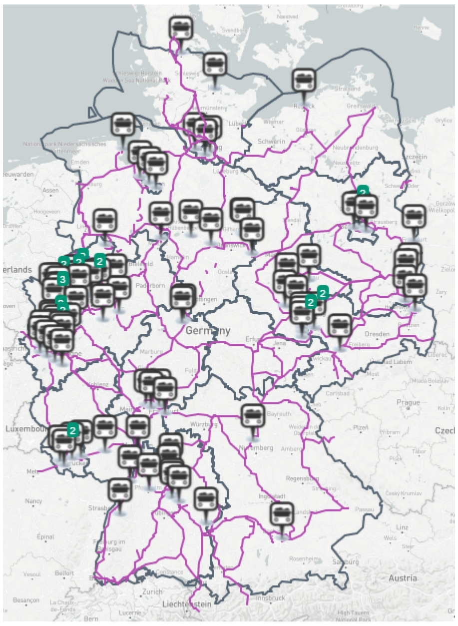

Figure 5.4: Germany exiting coal power plants (balloons) and connection to high-voltage transmission lines (purple lines) [Frauhoher ISE, 2021b].

Therefore, utilising such fossil power plants would save expensive connection costs and the costs associated with the power cycle. As shown above, once supplied by coal, the power cycle can be connected to a Carnot battery and would avoid the costs associated with the discharge (three times more than the charging ones). Thus the retrofitting of German coal-fired power plants could be an exciting option to study as Germany intends to phase out coal by 2030 and currently has 96 coal power plants that amount to 44 GW of installed capacity [Frauhoher ISE, 2021b]. The idea of including fossil fuel power plants as part of the energy transition could also bring social benefits. Retrofitting existing infrastructure could create a positive social impact of adapting coal power plant workers to the new green Carnot battery configuration. Hence, securing a just energy transition as social impacts are reduced.

5.3 Technical and economical data

The Siemens ETES has been seen as one of the most prominent Carnot battery technology as it is already commercially available. Moreover, it is based on 80% of mature technology and has successfully proven its concept in the German context [Siemens Gamesa, 2021a]. Another crucial factor taken into consideration was data availability.

The technical and economic data regarding the grid-scale technologies that will be simulated is visible on Table 5.3.

Table 5.3: Grid-scale energy storage technical and economic data. Own elaboration.

	Utility-scale battery Samsung 2030	**Utility-scale battery Tesla megapack**	**Carnot battery Siemens ETES**
Storage capacity for one unit (MWh)	7.0	3.1	130
Output power for one unit (MW)	21.0	1.5	1.4
Input power for one unit (MW)	3.5	0.8	5.4
Technical data			
Roundtrip efficiency (%)	96	94	45
Charge efficiency (%)	98.5	***80***	99
Discharge efficiency (%)	97.5	***90***	45
Technical lifetime (years)	25	20	*30*
Financial Data			
Price (M€/MWh)	0.6220	0.3943	0.0827
Price (M€/MW)	0.1600	0.0072	0.3309
Fixed O&M (% of Inv.)	0.54	**0.47**	***0.90***
Sources	Danish Energy Agency, 2020	Tesla, 2022	Dumont et al., 2020 and Wikipedia, 2021

A conversion rate that equals 1 USD to 0.88 EUR has been assumed. Moreover, regarding the ETES, it has been assumed a lifetime expectancy of 30 years and a fixed operation and maintenance of 0.9, corresponding to an electrical heater [Wikipedia, 2021]. In relation to the Tesla megapack the discharge and charge efficiency and fixed costs are assumed to be the same as the ground option in the EnergyPLAN.

Regarding the retrofitting of coal-fired plants, the technical parameters were assumed to be the same for all tested options, equal to the Siemens ETES and the economic consideration are represented in Table 5.4.

Table 5.4: Economic data of retrofitting with Carnot battery. Own elaboration.

	Carnot battery Siemens ETES	**Retrofit - EES CORE**	**Retrofit - EES Simens Switch**
Storage capacity for one unit (MWh)	130.0	130.0	140
Output power for one unit (MW)	21.0	1.5	140
Input power for one unit (MW)	3.5	0.8	140
Financial Data			
Charge (M€/MW)	0.08272	0.08272	0.08272
Discharge (M€/MW)	0.24816	0	0
Storage (M€/GWh)	82.72	82.72	0.04
Sources	Dumont et al., 2020	Siemens Gamesa, 2021b and	Recharge, 2021

Chapter 6

Economic and Technical Evaluation

In this Chapter, the scenarios used as a base are scrutinized. Moreover, the results obtained from the simulation through the EnergyPLAN and with the assistance of Matlab are presented.

6.1 Base model scenarios

As mentioned in the Methodology (Chapter 4), it was decided to utilise already built scenarios in Heat roadmap Europe as the origin to obtain three pathways for 2030. The already built scenarios were the Baseline 2015 (BL 2015), the Baseline 2050 (BL 2050), and the Conventionally Decarbonised (CD 2050).

Nonetheless, there is a drawback in utilising already built scenarios after all the EnergyPLAN models were performed in an old version. Figure 6.1 visually represents this discrepancy when one compares the primary energy supply (PES) from the scenarios that are run in the previous version to the outcomes obtained in the recent version.

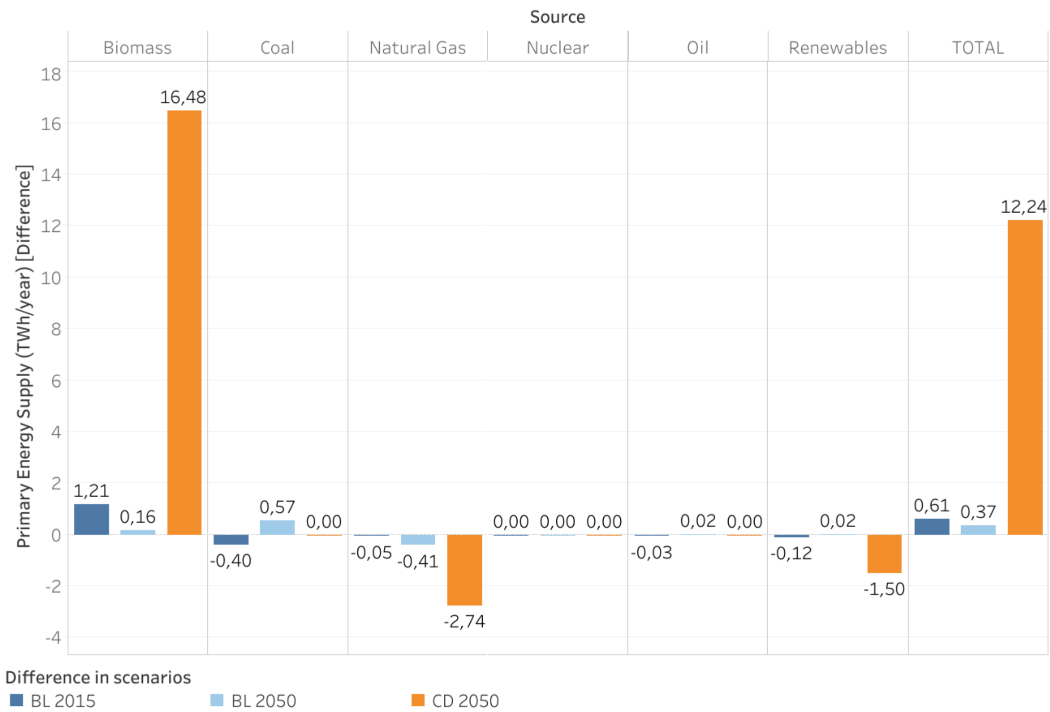

Figure 6.1: Difference in PES when comparing the scenarios with a new version. Own elaboration. Notes: Bl = Baseline; = Conventional decarbonised.

The conventionally decarbonised scenario is the one that evidences more changes, with an increase in biomass consumption and a decrease in the consumption of natural gas and renewables. However, this impact is minimal compared to the total amount of PES, with an equivalent growth of 0.4% from the previous PES. The baseline scenarios for 2015 and 2050 present only slight alterations from being run in the most recent EnergyPLAN version.

The primary energy supply and the carbon dioxide emitted for each of the three mentioned scenarios is shown in Figure 6.2.

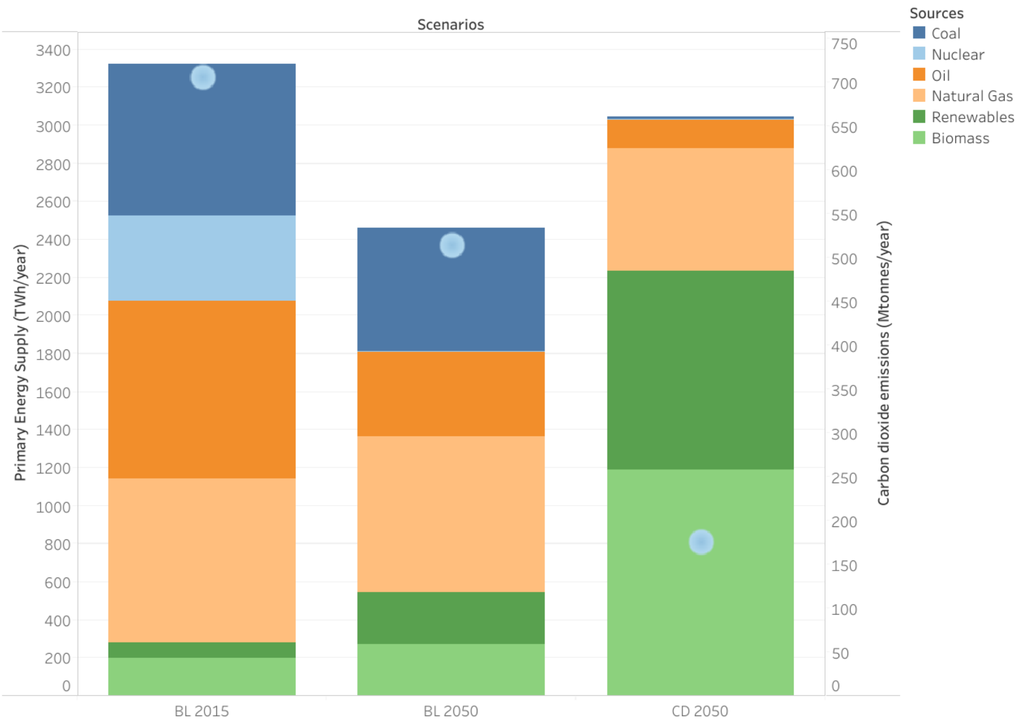

Figure 6.2: Primary energy supply and carbon emission of the baselines and decarbonised scenarios. Own elaboration.

Notes: Bl = Baseline; = Conventionally decarbonised.

As visible in Figure 6.2, the increased decarbonisation from the baseline to the CD 2050 scenario is done by, on the one hand, increasing the deployment of biomass and renewable energy, and on the other hand by the elimination of coal and reduction of oil boilers.

In addition to replacing coal, the CD scenario also considers the decarbonisation of the transport and industry sector. Thus, increasing the electricity demand altogether, as seen in Figure 6.3.

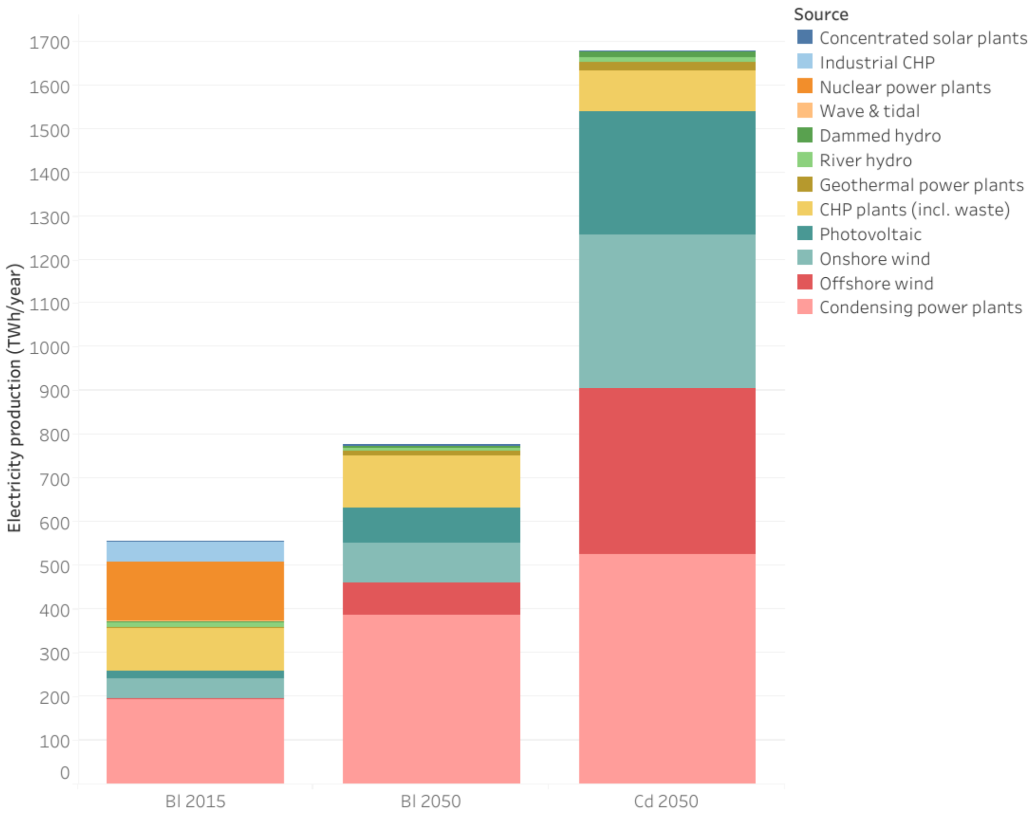

Figure 6.3: Electricity production in the different scenarios. Own elaboration. Notes: Bl = Baseline; = Conventional decarbonised.

Although the transportation and industry sectors are not the focus of this thesis, it is vital to consider their decarbonisation as their transition passes through direct electrification. Hence, the additional electricity demand and corresponding demand profiles should be considered since they directly impact the functional work of the power system.

As seen in the figure above, the decarbonisation of the CD and the consequent increase of renewable energy share carries some significant challenges. For instance, the CD's critical excess electricity production is equivalent to 73.37 TWh/year. In comparison, the BL scenario only has 0.3 TWh/year of electricity, which does not match the consumption. Meaning that if the CD scenario does not include any flexibility provider, this electricity would be equivalent to the yearly curtailment of renewable energy. Thus, it possible to state that through the inclusion of VRE, there is a crescent need for flexibility sources like the Carnot battery.

6.2 Pathways

The different pathways for 2030 were obtained to test the impact of storage technologies in several possible futures perspectives. The primary energy supply of the three pathways created (BL, CD and EH) for the year 2030 have been visually represented in Figure 6.4 in order to compare to the already existing scenarios.

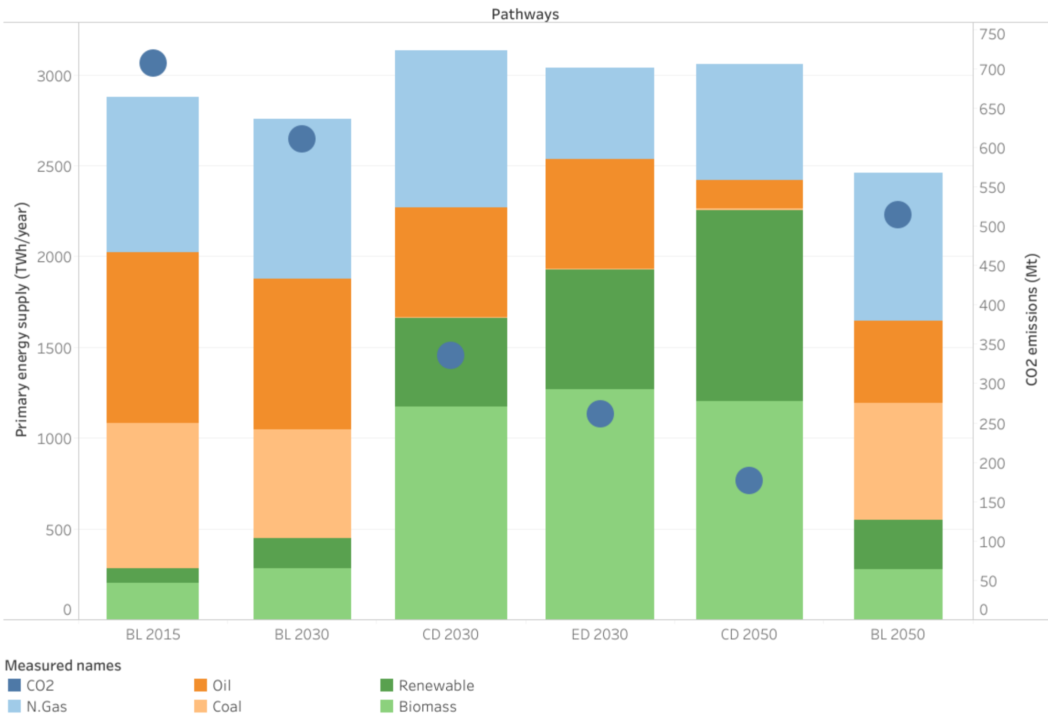

Figure 6.4: Primary energy supply and carbon emission in the utilised pathways. Own elaboration.

The baseline pathway for 2030 only accounts for 16% of renewable energy in the energy mix, this share is increased to 53% on the CD and to 64% in the EH pathway.

Among the three 2030 pathways, the Enhanced decarbonised (ED) is the one that presents a lower carbon dioxide emission since it raises the CD ambition and ensures total decarbonisation of the power sector. The electricity mix of the three pathways is represented in Figure 6.5.

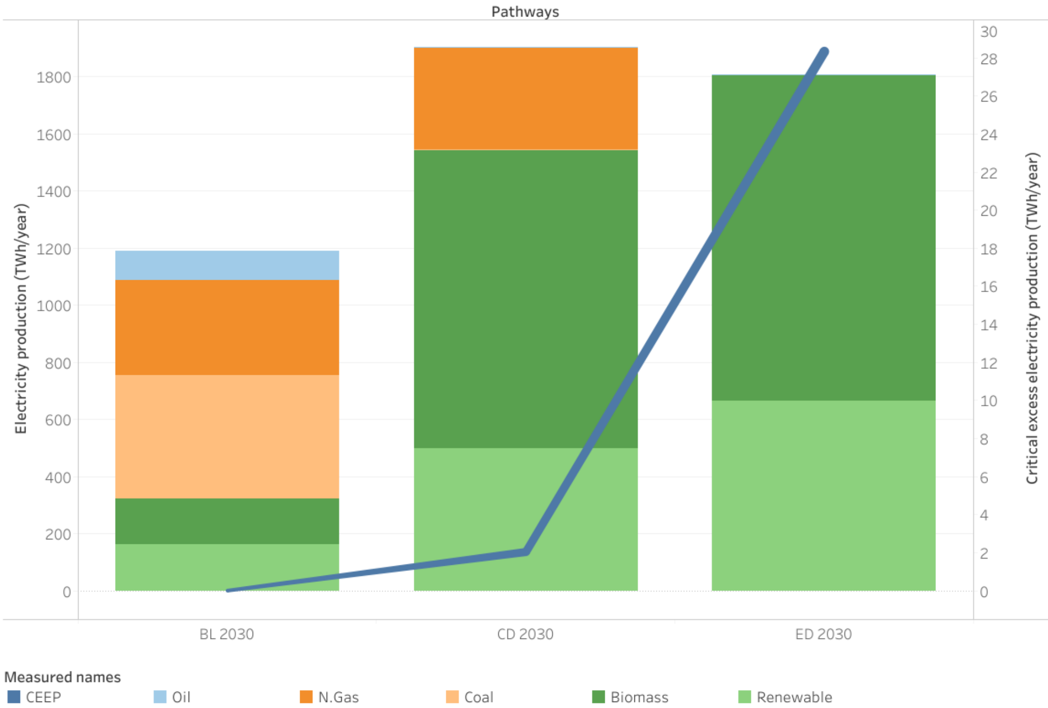

Figure 6.5: Electricity production mix in the different 2030 pathways. Own elaboration.

In the EH power system's decarbonisation, a maximum biomass consumption equal to 1200 TWh/year was assumed. This maximum value corresponds to the HRE scenario for 2050. Hence it is understood that the sustainable level of biomass is maintained. The challenge of adding higher shares of renewable energy in the power sector, in the EH case up to 100%, is represented by the significant increase of the CEEP factor in the right vertical axis. The decarbonisation of the power sector effectuated from the CD to the EH pathway created an additional 26.3 TWh/year electricity production that the system has not absorbed. Hence, if no balancing services are provided, this amount of renewable electricity would have to be curtailed. Therefore, the additional excess production seen in the EH pathway makes this option the most promising for Carnot batteries.

6.3 Storage technologies

The two applications identified for Carnot batteries in the power sector will be presented in this section.

6.3.1 Gird-scale storage

Two grid-scale lithium-ion solution have been tested in the the three pathways developed. This two options, the Tesla and Samsung represent the direct competitors in this application. The evaluation of the Samsung battery is visible in Figure6.6.

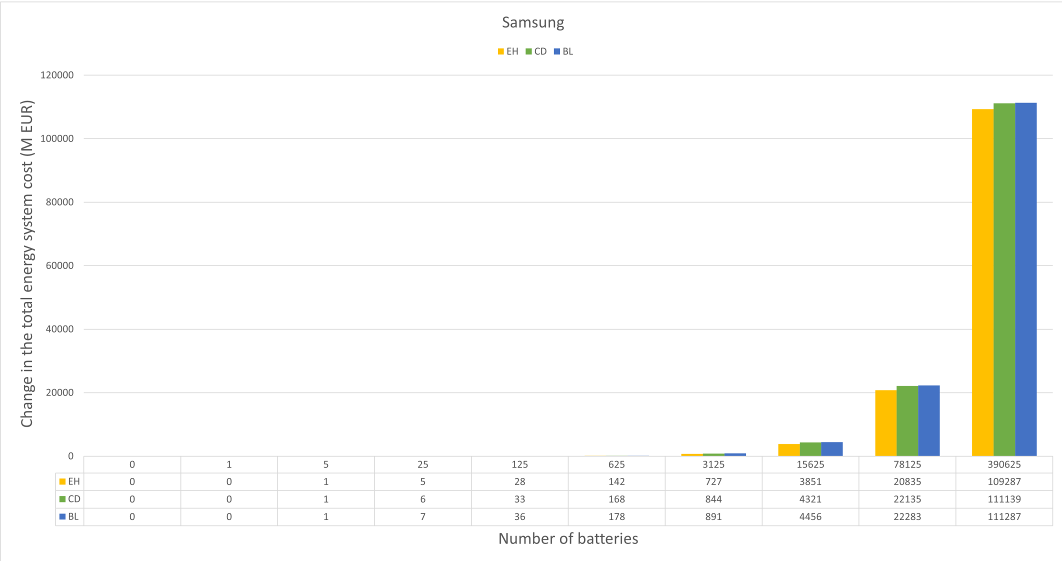

Figure 6.6: Samsung grid-scale storage in the three pathways. Own elaboration.

As can be seen, this solution is not economically feasible since the associated costs are more significant than the benefits that it brings to the overall energy system, increasing the total annual costs. Moreover, the statement that the EH pathway would be the most promising pathway to storage technologies can be proven as the ED change in total energy system costs are the ones that represent a smaller difference.

The same situation of economic unfeasibility occurs in the Tesla battery, as seen in Figure 6.7.

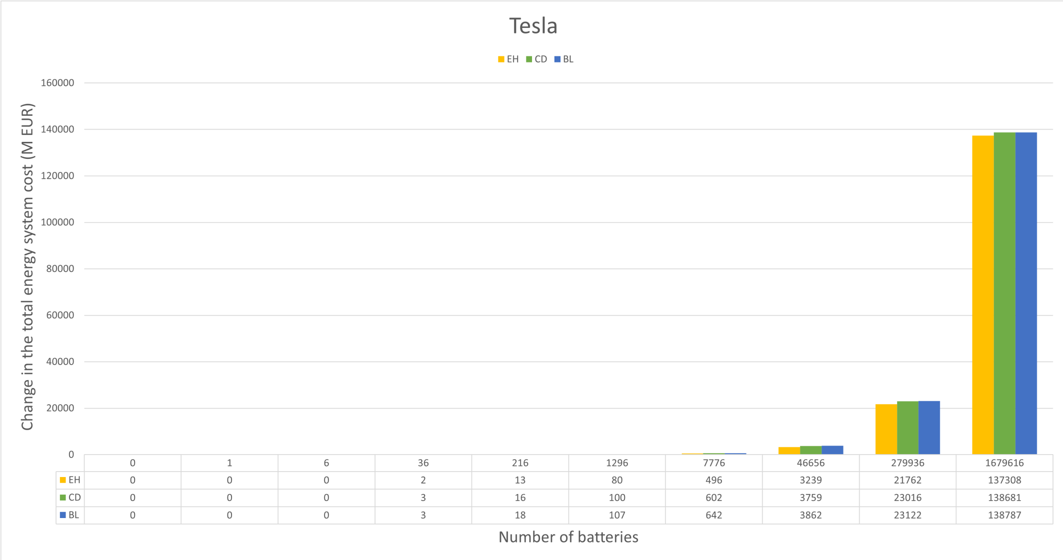

Figure 6.7: Tesla grid-scale storage in the three pathways. Own elaboration.

The Carnot battery solution tested to perform a grid-scale application was the Siemens ETES. Moreover, even considering the possibility of increasing the storage capacity independently of the charging and discharging power, it was impossible to prove its economic feasibility. The performance obtained of this technology in the EH pathway is represented in Figure 6.8.

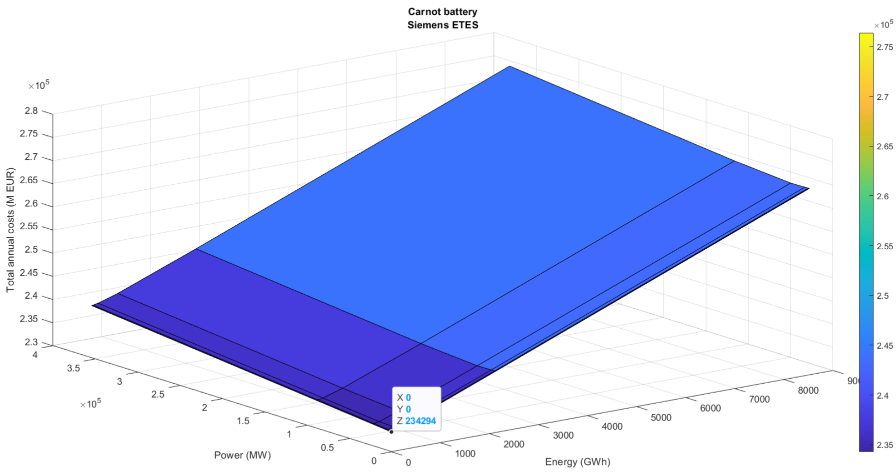

Figure 6.8: Siemens ETES in the ED pathway. Own elaboration.

The economic impracticability is shown as the least costly option is the one that considers zero capacity storage and zero charging and discharging power.

6.3.2 Retrofitting of coal-fired power plants

Three options have been tested regarding the retrofitting of coal-fired power plants application. The first is the assumption of a Siemens ETES solution connected to a discharging already existing infrastructure. Therefore, compared to the grid-scale Simemens ETES solution, the discharge cost is assumed to be zero. The evaluation of such an option in the EH pathway is visible in Figure 6.9.

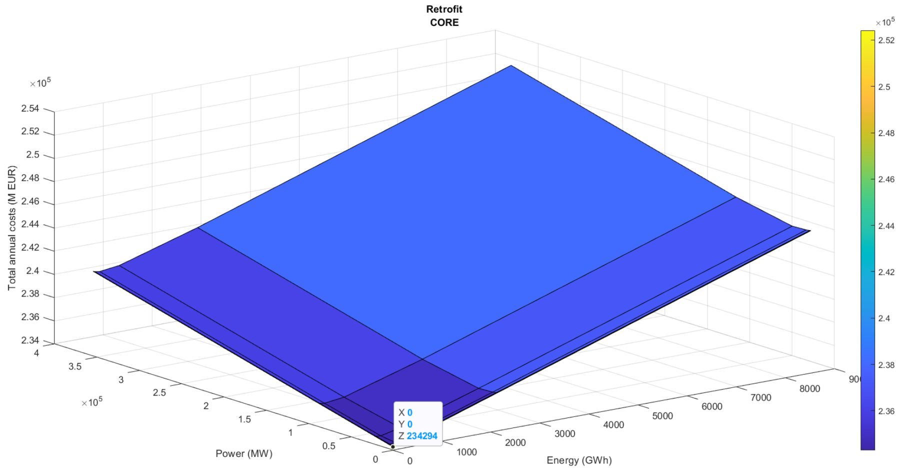

Figure 6.9: Siemens ETES connected to existing turbine to in the ED pathway. Own elaboration.

Once again, the optimal least costly option was the omission of the Carnot battery. The same discouraging result was obtained for the CD and BL. However, only the EH has been presented as the most promising pathway for including electrical storage. If the Carnot battery feasibility is not proven in the EH, it will not be in the BL and CD.

The second tested option was the Siemens Switch, that present a incredible promising low cost accordingly to the company. With the assistance of Matlab, it was possible to obtain the best-case scenario for a Switch configuration in Germany. The simulation that has been run did not include any restrictions besides the maximum capacity that Carnot batteries could contribute in a given pathway. The results, as seen in Figure 6.10, show that this solution can be economically feasible.

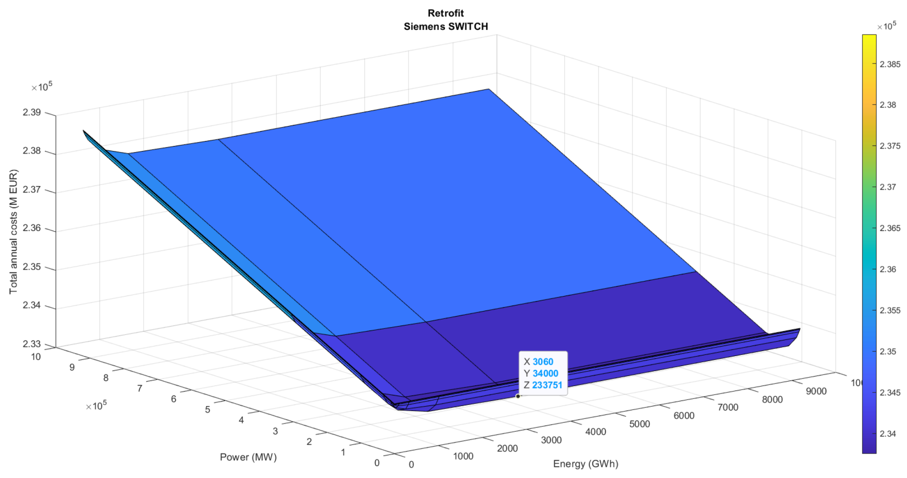

Figure 6.10: Siemens Switch in the ED pathway. Own elaboration.

The results obtained demonstrate that the optimal solution to ensure the least costly energy system solution occurs when one considers a charging and discharging power equal to 34 GW and a storage capacity of 3060 GWh.

However, this option presents fundamental limitations as it assumes retrofitting existing coal-fired power plants. As mentioned in the State of the art, Germany currently has 96 coal power plants that amount to 44 GW of installed capacity, meaning that these would be plants that could be switched into green solutions. Considering this limitation, the discharging power of the 96 power would equal approximately 314 Switch green power plants. This simplification considers that each 96 coal-fired power plant had an average 458 MW installed capacity, which does not correspond to reality.

Keeping in mind that the feasibility of the retrofitting plants could be improved by increasing the storage capacity it was tested, the optimal storage capacity for the maximum charge and discharge power was restricted by the amount of coal-fired power plants available. The relation between the total annual costs of the system and the storage capacity of Carnot batteries is visible o Figure 6.11.

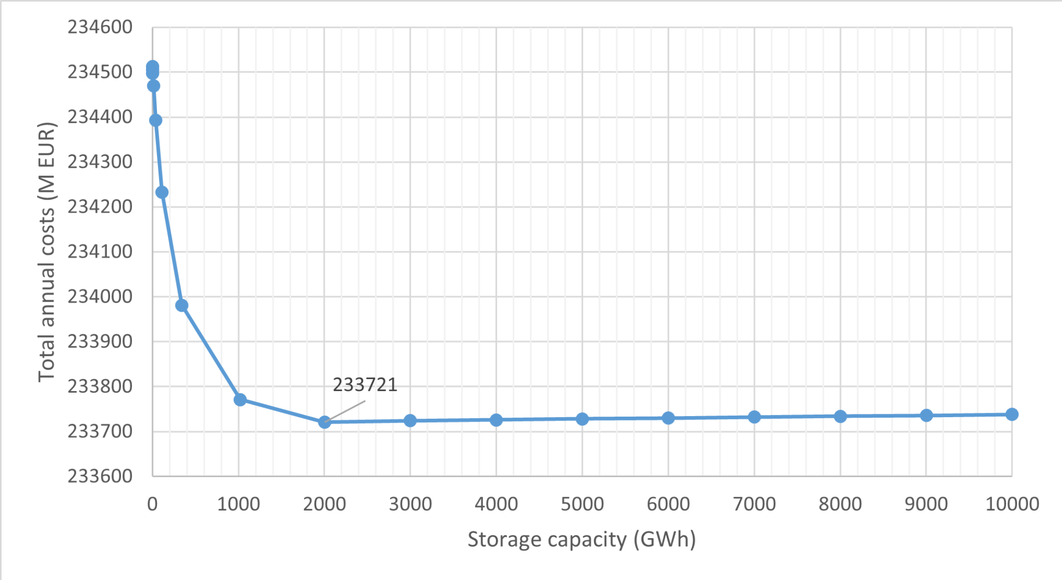

Figure 6.11: Total annual costs and storage capacity for the maximum discharge. Own elaboration.

As seen above, the optimal storage capacity would be 2000 GWh. This new configuration would ensure that the total annual costs could be reduced by 570 million, compared to the initial scenario. If the same ratio of power and energy was maintained and the storage capacity was not increased, the system would still benefit from a 365 million euro reduction.

The technical differences of maintaining the mentioned ratio or being able to increase the storage capacity are shown in Figure 6.12. As seen, the additional storage capacity ensures a more significant CEEP reduction when compared to the EH pathway without any Carnot technology. The larger storage capacity allows the Carnot to charge more closely to VRE excess electricity, increasing the Carnot's charging electricity consumption and decreasing the CEEP. Moreover, this balancing service diminishes the use of biomass, therefore, reducing the total amount of primary energy supply required.

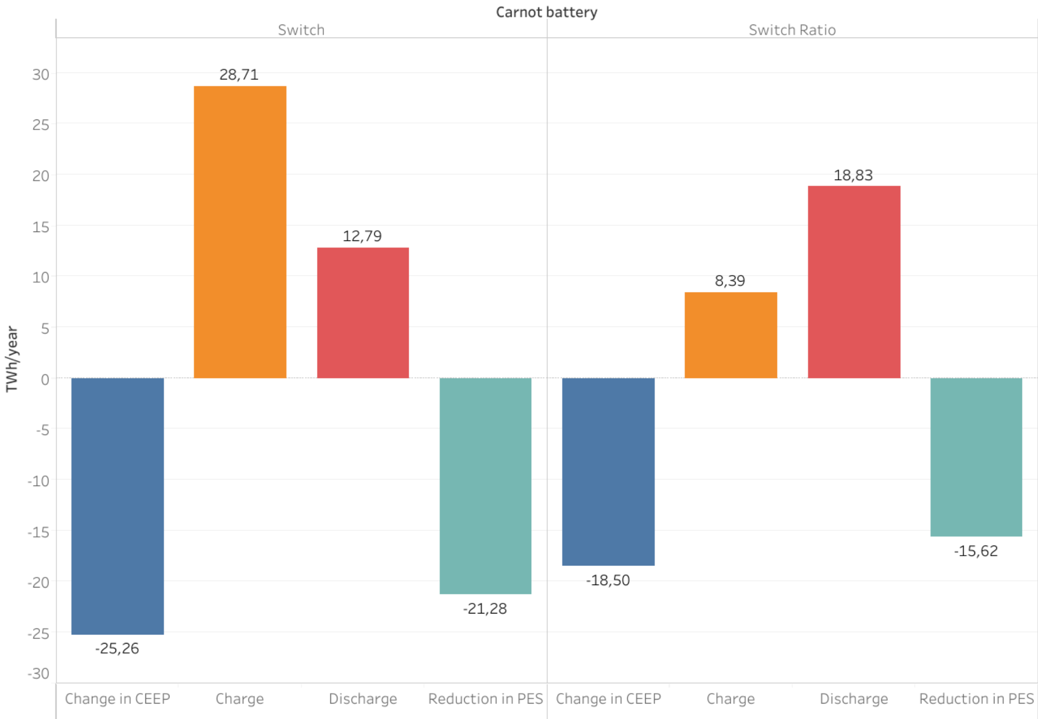

Figure 6.12: Savings in the different pathways in regards to the technologies evaluated. Own elaboration.

The third and last retrofitting option was the assumption of a Carnot battery with the same configuration as the Siemens ETES but with the Siemens Switch costs. The economic feasibility of these options is represented in Figure 6.13. This solution also assumes a limited installed discharged power available from existing coal-fired power plants, which would be 31428 ETES systems, higher than the current optimal amount of ETES.

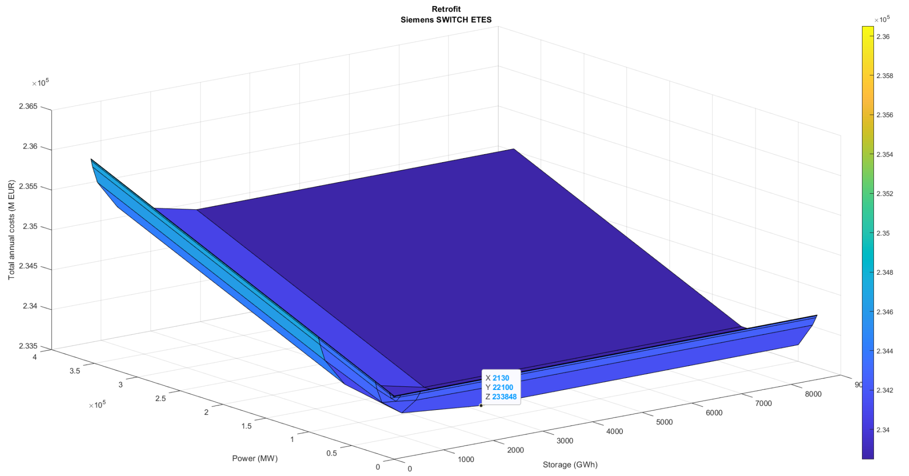

Figure 6.13: Siemens SWITCH cost assumption using ETES in the ED pathway. Own elaboration.

The economic feasibility of the three grid-scale tested technologies, three retrofitting options on the three pathways are visible in Figure 6.14.

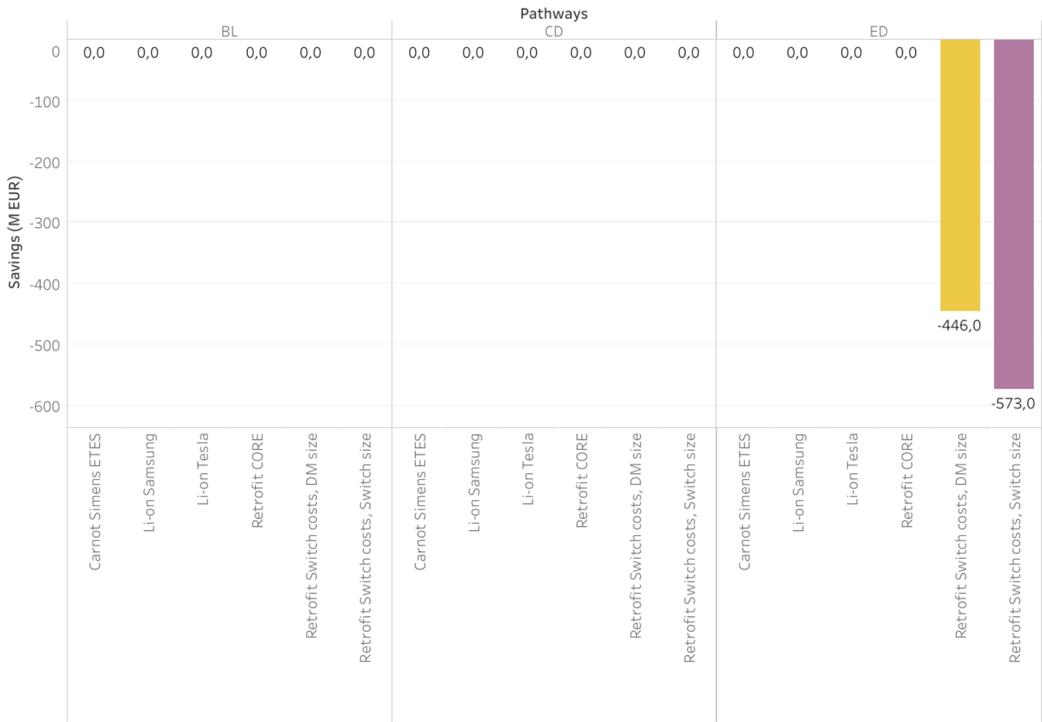

Figure 6.14: Savings in the different pathways in regards to the technologies evaluated. Own elaboration.

6.3.3 Sensitivity analysis

In order to assess the impact of assuming the simulation of all pathways in island mode, a sensitivity analysis regarding the transmission line capacity was performed. This sensitivity analysis has taken into account the two economical feasible options from the previous section. The method utilised to perform this sensitively is described in the methodology. Furthermore, it is relevant to note that the predicted German transmission line capacity for 2030 is about 35.3 GW [BMWi, 2017].

For the ETES case, it can be seen in Figure 6.15 that the best scenario for the Carnot solution would be with no connection to an external market. Nevertheless, if one considers the addition of transmission lines, the solution is still feasible until capacities are lower than those predicted for 2030.

Number of Simens ETES	Transmission line capacity (MW)									
	0	6198	12396	18595	24793	30991	37189	43387	49585	55784
0	234294	234741	235160	235566	235991	236410	236821	237234	237644	238050
1	234293	234741	235160	235566	235991	236410	236821	237234	237644	238050
3	234293	234740	235160	235566	235991	236410	236821	237234	237644	238050
9	234292	234739	235159	235565	235991	236409	236821	237234	237644	238051
27	234287	234733	235156	235562	235989	236408	236821	237235	237644	238051
81	234267	234711	235142	235552	235982	236405	236820	237236	237647	238055
243	234191	234641	235094	235517	235962	236396	236821	237242	237657	238068
729	233942	234435	234975	235455	235943	236408	236852	237289	237716	238135
2187	**233849**	234489	235168	235693	236210	236696	237156	237603	238037	238461
6561	235175	235817	236497	237023	237541	238026	238487	238933	239367	239791

Figure 6.15: Sensitivity analysis of the transmission line impact in the ED pathway considering Siemens ETES. Own elaboration.

For the Siemens Switch case, represented in Figure 6.16, the results are similar. However, the impact of the transmission line is felt with lower capacities.

Number of Simens SWITCH	Transmission line capacity (MW)									
	0	6198	12396	18595	24793	30991	37189	43387	49585	55784
0	234294	234741	235160	235566	235991	236410	236821	237234	237644	238050
1	234291	234739	235159	235565	235990	236409	236821	237234	237644	238051
3	234287	234734	235156	235563	235989	236408	236821	237235	237645	238052
9	234274	234720	235149	235557	235984	236406	236820	237235	237646	238054
27	234238	234686	235127	235541	235972	236400	236820	237239	237652	238062
81	234141	234607	235075	235501	235947	236394	236827	237254	237674	238090
243	**233967**	234471	235001	235476	235969	236441	236894	237336	237767	238190
729	233977	234574	235232	235758	236275	236761	237221	237668	238102	238526
2187	234926	235568	236249	236774	237292	237778	238238	238684	239118	239542
6561	237979	238621	239301	239827	240345	240830	241291	241737	242171	242595

Figure 6.16: Sensitivity analysis of the transmission line impact in the ED pathway considering Siemens Switch. Own elaboration.

Chapter 7

Discussion

In this Chapter, the discussion of the theoretical approach, methodology, and results obtained are presented, accompanied by considerations of the assumptions performed.

7.1 Theories

In this thesis, two theories were combined to obtain a more comprehensive view of the challenges and opportunities of an energy transition. The Carbon lock-in theory explains the mechanics that reinforce the fossil fuel technological lock-in. The infrastructure lock-in associated with sunk costs was relevant as it guided the course of this study into the retrofitting of coal-fired power plants. Afterwards, what once could be seen as a deterrent to the energy transition may help increase the economic feasibility of clean technologies, as the discharging part of a coal-fired power plant could be reused.

On the other hand, the Multi-level perspective theory has been instrumental in representing long-term dynamics as the one analysed and how changes from one fossil socio-technical system to a renewable one can occur. Furthermore, MPL has shown that niche technologies like Carnot, which are now in the first experimentation phase, could disrupt the current technological lock-in. For Carnot technology to be institutionalised by 2030, it must find a mainstream market and prove its economic and technical advantage over competitors. Moreover, it was also paramount to understand the symbiotic evolution of technologies and society and how climate crises can open windows of opportunities to niche technologies.

The theoretical approach was delimited to the technological and infrastructure lock-in on the socio-technical system. Therefore, the other dimensions that also impose inertia to change like markets, user presences, policy, science and culture were not included. This delimitation simplifies the socio-technical system to simply technical hence it is inferred that further research should include the reaming dimensions. The simplification of the socio-technical system as only technology could mean that by including more layers of lock-in dimensions, the feasibility of the Carnot battery could be compromised. For instance, considering market implications and external market prices could make Carnot battery grid-scale storage impracticable. The uncertainty of possible implications of an external market competitor were tested in the sensitivity analysis.

7.2 Methods

7.2.1 Literature review

The Carnot concept is not recent, though the development of this concept into defined categories and available technological options is. Considering that the only literature found that concretely defined Carnot batteries dated 2020 demonstrates this novelty aspect and the difficulty of summarising information under the big Carnot battery umbrella.

Another difficulty found was the available information regarding available technology options. After studying the different technology readiness levels, it was possible to deduce that the commercialisation phase is only starting with proven technologies at level nine. This fact increases competition between companies as there is no market price for Carnot batteries, increasing the challenge to obtain available information. This uncertainty regarding the costs was attempted to be overcome by testing different solutions, namely 6 in the three different pathways, amounting to 21 pathways.

7.2.2 Energy system analysis tools

It was understood that a simulation approach rather than an optimisation would be ideal for comparing several electrical storage technologies in order to evaluate Carnot batteries' economic and technical feasibility. Using an analytical simulation tool as the EnergyPLAN allowed the design of several pathways that correspond to different possible 2030 energy visions. Moreover, it permitted the addition of storage technology options and the evaluation of the particular impact of each assumption. Therefore, it was concluded to be the most suitable option to simulate Carnot technology and competitors in a smart energy system. However, since the EnergyPLAN is a simulation tool, it has few optimisation options, as it only allows critical excess regulation strategies and selection of the simulation strategy (technical or market simulation). Therefore, it was presumed that the link of the EnergyPLAN with Matlab would be a precious complement. The utilisation of Matlab permitted the optimisation of the several simulations obtained in the EnergyPLAN. Hence, acquiring the benefits of a simulation and optimisation approach.

A drawback of utilising the EnegyPLAN is that it does not consider spatial limitations or national geography. This fact is significant due to the available distributed renewable energy resources, such as the wind in the north of Germany. However, this factor is decreased in this analysis as the Siemens ETES functions as a virtual power line, meaning that because of its unrestricted geographical nature, it can be collocated near the vastest wind production located in the north and help balance the fluctuation of the production. Hence, decreasing the possible transmission line costs associated with a unified grid to balance the production and demand. In this sense, EnergyPLAN underestimates this valuable geographical independent characteristic of Carnot batteries.

Matlab as an auxiliary tool attained the optimal storage capacity and power according to two defined optimisation strategies. In the case of Lithium-ion batteries is not possible to increase the storage capacity without adding more batteries in series or parallel. On the other hand, Carnot batteries can independently increase their capacity since the electrical energy is stored thermally. These two optimisation strategies, one that guarantees a ratio between power and capacity and the decoupling of both, permitted the evaluation of this specific Carnot batteries advantage.

7.2.3 German 2030 energy pathways

In the analysis of this thesis, it has been decided to utilise already built scenarios as guidelines for creating three pathways. This decision has taken into account that the principal aim of this study is not to assess the German energy mix by 2030 but to evaluate the impact of different storage technologies. However, the utilisation of already built scenarios has some limitations. The first is that such HRE scenarios were developed in previous EnergyPLAN versions, meaning that updated versions contain alterations that impact the outcomes obtained. This impact was evidenced when one had to add 3 MW of CHP installed capacity to the BL 2050 scenario to avoid the state of critical import. However, the analysis of the differences from using distinct versions was conducted, and it was possible to conclude that even in the CD scenario, the most affected, the changes were minimal (0.4%) compared to the total primary energy supply.

The energy pathways for Germany were based on a linear regression from existing scenarios. This option has been chosen due to time constraints and because this thesis's priority is not a simulation of an energy system scenario but the evaluation of the inclusion of Carnot batteries. However, utilising already built scenarios as a baseline has been seen as favourable since they were created in a study group that carefully analysed the assumptions and results.

A linear regression approach was used to obtain two 2030 pathways, taking into account the existing 2050 BL and CD and the 2015 BL. This simplified energy transition approach has some limitations as the timescale and evolution of the energy system is not linear, nor the technological improvements. This factor of the non-linear energy transition has given the need to create a third pathway where the power sector, which is the focus of this thesis, would be decarbonised. In this sense, the EH pathway represents an enhanced electricity decarbonisation from a linear approach.

The EH pathway has included a different primary energy supply. However, the distribution of demands also impacts the configuration of the pathway. In this regard, no further assessment was performed on how different demands would impact the 2030 pathways. However, one can evaluate the possible flexibility sources that could decrease the need for storage and, therefore, compromise Carnot batteries' feasibility. Examples of possible flexibility sources per demand are represented in Table 7.1.

Table 7.1: Matrix of possible flexibility sources per demand. Own elaboration.

Demand	**Flexibility sources**
Power	Transmission line capacity Flexible demand
Heating and cooling	Individual HP and EH District heating Distribution curve
Transport	FCEV EV (dump charge) V2G (smart charge)
Industry	Hydrogen flexible production
Water	Flexible desalination

The flexibility sources represented in the table above could serve as a base for future work in creating a more flexible pathway, therefore, testing the limits of Carnot battery feasibility.

Another inherent characteristic of the already built scenarios that impact the outcomes is the simulation in island mode. The fact that all pathways do not consider any connection to external electricity markers might mean that some installed capacity is over-dimensioned as the transmission line would ensure additional flexibility. Without the possibility to import and export electricity, internal sources of flexibility would have to be used, hence being the optimal case for Carnot batteries. Nevertheless, on the account that the power sector is the main focus, a sensibility analysis of the transmission line capacity was effected.

7.2.4 Carnot battery simulation

Carnot batteries have been simulated as electrical storage, characterized by charging and discharging power and storage capacity. This simplification was chosen as a direct comparison method to other electrical storage technologies such as lithium-ion. However, this assumption has its downsides as it disregards other possible applications for Carnot batteries than electricity. It has been shown in the State of the art that Carnot batteries could also supply heat and process steam. Hence, it could also have applications in the heating and cooling sector, connected to district heating. Moreover, it could supply process heat to industrial processes and use the excess heat to increase round-trip efficiency. Theoretically, the heat produced could also be used in the thermolysis process to produce hydrogen that could supply transportation or industry, and to perform thermal desalination to fulfil water demand.

Therefore this is an initial conservative estimation of the Carnot battery potential since further studies that would include more applications could encounter feasible niche applications or additional revenue streams that would improve the feasibility of the tested applications.

7.3 Evaluation of technical and economical feasibility

The lithium-ion solutions were not considered economically feasible in the tested pathways. The same can be stated to the Siemens ETES performing a grid-scale application. However, the picture changes when considering the low costs related to the retrofitting of coal-fired power plants. In this case, the Siemens Switch solution was proved to be economically feasible in the EH pathway. Nevertheless, the costs associated with the Siemens Switch are a rough assumption of what could be the cost of retrofitting all German coal-fired power. Therefore, a more detailed study of the existing coal power plant and correspondent feasibility would be necessary.

The simulation with the Siemens ETES solution assuming the Siemens Switch costs was performed to assess the feasibility of retrofitting coal-fired power plants in smaller, modular solutions. This was the solution found to overcome the discrepancy in 96 coal-fired power plants. It was concluded that the solution could also be economically feasible but less attractive than more extensive Switch solutions.

The Carnot batteries present a substantial sustainable advantage, particularly when one compares with Lithium-ion batteries, the main competitor on the market. Carnot batteries can thermally store electricity in cheap, abundant and non-harmful materials, such as water, rocks, or salts. In addition, it has been shown the beneficial aspect of being able to decoupled the storage capacity from the charging and discharging power. In the Switch example, if the ratio of power over capacity was followed the total annual savings would amount to 365 million euros comparing to the 573. Moreover, the additional storage capacity has also allowed a better technical performance as the amount of CEEP reduced as increased from 15.62 to 25.26 TWh/year.

The sensitivity analysis of the transmission line capacity has shown that taking into account the EH pathway characteristics and an average electricity market price equal to 51 EUR/MWh, the Siemens retrofitting solution continuous to the economically feasible. The economic feasibility is compromised when considering transmission line capacities over 37 GW. However, the planned transmission line capacity for 2030 is 35.3 GW.

Chapter 8

Conclusion

The urge to decarbonise the German electricity sector has led to the ambitious goal of having 80% of the electricity supplied by renewable share by 2030. Due to the high fluctuation of renewable interment sources, this energy transition brings several challenges, including a significant need to balance the power sector. Nowadays, lithium-ion batteries are the most deployed electrical storage technologies. However, their elevated cost has imposed some restrictions on a more significant role. Therefore, it is a need to test niche and alternative innovations of electrical storage such as Carnot batteries.

This dilemma has led to Research Question:

What are the applications and the impact of Carnot batteries use to increase renewable energy penetration in electricity by 2030?

In order to properly answer this problem formulation, three underlining research questions have been formulated.

What is the maturity associated with the different Carnot batteries configurations?

The Carnot battery concept applied to technological options is recent, and this new term is seen as an umbrella of different possible configurations. Therefore it was first necessary which configuration would be possible inside the three main parts of a Carnot battery, power to heat, thermal energy storage, and heat to power. Afterwards, it was possible to ground these configurations and assess their technology readiness level. It was concluded the most mature configurations were the electrical heater combined with a Rankine cycle, liquid air and heat pumps and Rankine cycles.

Which applications could contribute to a renewable electricity penetration increase?

The Carnot battery can have several ouputs, namelly process steam, heat, and electricty. Therefore, it can also perform a myrad of applications. However, due to the focus of this thesis on the power sector, only the grid-scale storage application and the retrofit of coal-fired power plants were consider.

Concerning the grid-scale application, it was found that unrestricted geographical conditions that Carnot batteries present could be a benefit. This factor is highly relevant compared to other solutions such as CAES. In addition, the typical design of large scale capacities entitles the theoretically capacity for Carnot batteries to work as virtual power lines, differing expensive grid reinforcements when located close to renewable energy production and avoiding grid congestion. Two practical examples were found of this application the HighView power and the Siemens ETES. The last one has been evaluated since it was possible to gather the required technical and economic data.

Regarding the retrofitting of coal-fired power plants, only case studies were found. Different solutions were proposed, being the one study in the Chile case of using a typical configuration of Concentrated solar plants with molten salt storage, electrical heater and steam generator. Nevertheless, a Siemens solution named Switch includes an electrical heater and storage in volcanic rocks. Once again, the Siemens Switch solution was tested as the supplier had more information available.

How could Carnot batteries be a technical and economical solution in Germany by 2030?

After the simulation of three different pathways and the optimisation of two lithium-ion grid-scale technologies and the Siemens ETES, it has been concluded that none of the presented options has competing for costs as the economic feasibility regarding the tested pathways was not evidenced.

Three additional retrofitting solutions including Carnot batteries configuration were tested. The costs assumption were varied accordingly to the CORE study, however, the most promising solution was the Siemens Switch. This solution was verified as both economic and technically feasible, decreasing the total annual system costs by 573 million euros. Moreover, it also allowed the decrease of 28.71 TWh/year o electricity export and the reduction of 21.28 TWh/year in the primary energy consumption. Therefore, answering directly to the sub-question, Carnot batteries could be a technical and economical solution when used to retrofit coal-fired power plants. This promising result should be assessed considering the uncertain level of the costs assumptions since it portrays a niche technology with minimal available information. However, there is a clear space for electrical storage technologies and an opportunity to reuse fossil fuel infrastructure, positioning Carnot batteries in a noteworthy position.

Chapter 9

Reflections

From a theoretical framework point of view, future research could include more socio-technical dimensions such as industry, markets or policies. This study could assess the current policies, barriers or incentives for emerging technologies like Carnot. Similarly, a market study of the options available would be a significant income to consider. Lastly, an analysis of the possible decarbonisation of industry throughout the Carnot could also evaluate a potential market since there are few options for supplying green process steam. This decarbonisation of industry would be especially relevant in the German context as there is a robust industrial culture.

Furthermore, a more detailed study could also include a scrutinised analysis of the existing coal-fired power plants characteristics and individual feasibility studies since the size of the power plant could compromise the feasible application of Carnot solutions.

Moreover, additional Carnot battery applications could be studied related to the eventual possibility to supply heat and process steam. As mentioned above, green process steam is a significant need in Germany, but this heat could also be used to be produced by-produced. Examples of theoretically possible options would be the production of hydrogen through thermolysis or thermal desalination to obtain fresh water. The thermolysis could be especially relevant in the German context as Germany energy transition plans appoint to become one of the biggest European importers of hydrogen.

In addition, other Carnot technologies groups such as liquid air or the CHESTER project could be attractive alternatives to test since these options have different performance characteristics and applications. Concretely, the combination of the CHESTER project with the district heating could bring more flexibility to the system, and this configuration could also utilise the excess heat to increase round-trip efficiency. Once more, this option could be attractive as Germany has available district heating infrastructure.

The forthcoming analysis could also include the impact of the decarbonisation of other sectors besides the power sector, such as the transportation, industry and heating sector. This decarbonisation would also pass for electrification of some demands, meaning that the electricity demand and likely critical excess production from renewable would increase. Additionally, it would also be interesting to develop a pathway that would include all flexible sources mentioned in the Table 7.1 to assess the Carnot battery technical role in a more flexible, hence competitive environment.

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Appendix A

Sectoral description of pathways

Power sector

On Table A.1 the electricity demand, flexible demand and the imports and exports are represented for each scenario.

Table A.1: Power sector. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**
Electricity demand (TWh/year)	460.06	554.75	758.40	500.64	587.92
Flexible demand (TWh/year)	33.68	27.94	27.94	31.22	31.22
Import/Export (TWh/year)	0.00	0.00	0.00	0.00	0.00

In both scenarios, no transmission line is considered, so there is no fixed imports or exports. Additionally, the increased decarbonisation in the CD 2050 is followed by an electricity demand increase, reflected in the CD 2030 pathway.

The electricity demand follows the distribution curve seen in Figure A.1.

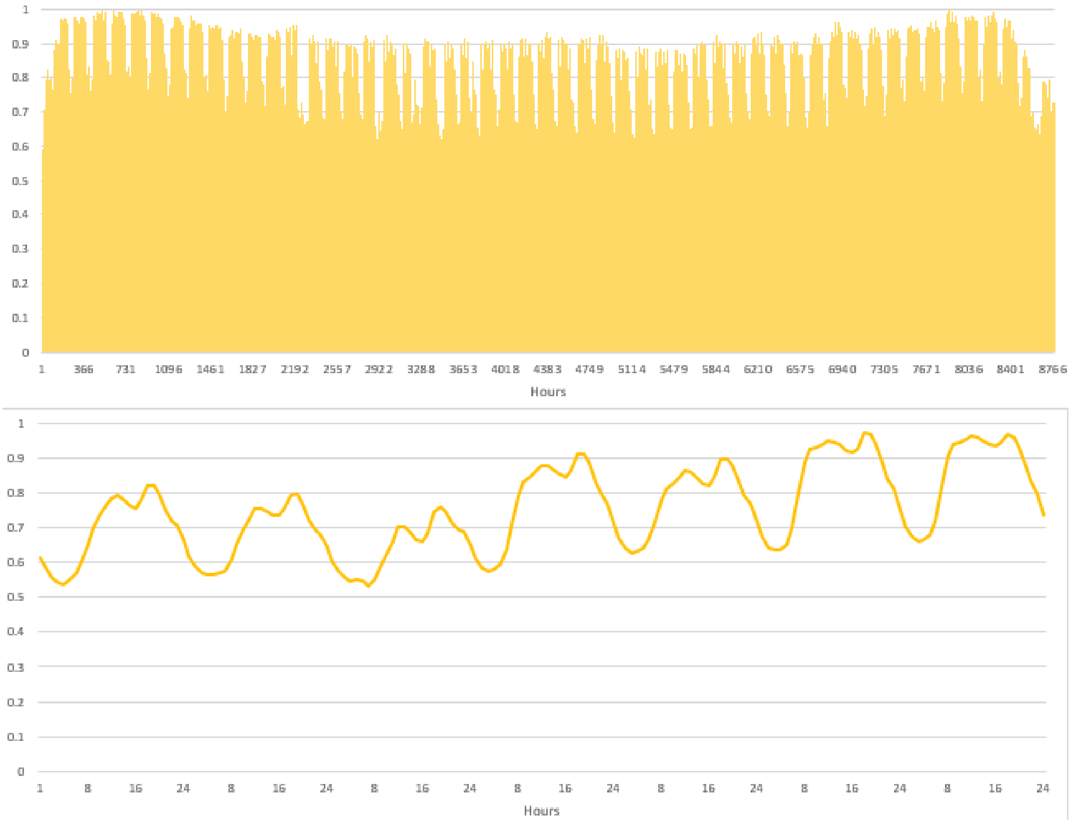

Figure A.1: Electricity demand distribution. Own elaboration.

The Figure on the top shows the electricity demand curve at all hours of the year. The demand curve is represented by a factor between 0 and 1 that is then multiplied by the electricity demand, creating the electricity demand fluctuation. As seen in the bottom Figure, the fluctuation occurs daily, with prominent peak demands related to leaving and arriving at home. These figure above portraits the challenge of matching the energy demand, that varies daily and suffer peaks in specific parts of the day, with a fluctuating energy supply from renewables.

The heat and electricity, namely the boilers and CHP, also impact the power sector. Therefore, the values of supply were obtained linearly, as represented in Table A.2 but the ones in italic were optimised to lower the total cost of the system and reduce unused capacities.

Table A.2: Heat and electricity. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decabornised (2030)**
Boilers	57260.4	57260.4	54920.4	***25185.0***	***36963.0***
CHP					
CHP (PP1)	89856.0	129003.0	243000.0	***100500.0***	***153700.0***
CHP elect.	18436.1	21207.6	21207.6	19623.9	19624.0
CHP thermal	23858.5	23858.5	23858.5	23858.5	***22077.0***
Industrial CHP					
CHP elect	50.2	0.1	0.0	28.7	28.7

In the ED pathway it was possible to decrease 200 MW of the CHP capacity in condensing mode due to the increased of VRE.

Hydrogen production also directly affects the power sector. In that sense, it has been optimised the least capacity installed to ensure the hydrogen demand. Therefore it represents a 370 MW installed capacity for the BL pathway and a 54 GW for the CD and the ED. The hydrogen storage was assumed to be 200 GW in the EC and CD pathways and 2 GW in the BL. These decisions were based on the least costly option for total annual system costs.

Heating sector

Table A.3: Heating sector. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**
			Individual Heating		
Coal (TWh/year)	11.45	0.00	0.00	6.54	0.00
Oil (TWh/year)	205.77	0.00	0.00	117.58	117.58
Natural gas (TWh/year)	291.31	223.91	223.91	262.42	262.42
Biomass (TWh/year)	61.96	14.03	14.03	41.42	41.42
Hydrogen (TWh/year)	0.00	0.00	0.00	0.00	0.00
Heat pump (TWh/year)	2.77	25.27	25.27	12.41	12.41
Electric heating (TWh/year)	43.04	35.93	35.93	39.99	39.99
			District heating		
Heat demand (TWh/year)	149.02	148.34	148.34	148.73	155.27
			Total heat demand		
Total demand (TWh/year)	**765.32**	**447.48**	**447.48**	**629.10**	**629.10**

Since the Baseline and the Decarbonised in the 2050 scenario have the same heating demand, the corresponding 2030 would also be equal, which means that a coal demand for individual heating would exist in the Decarbonised scenario equal to 6.54 TWh/year. However, since coal consumption is not in alignment with the 2030 goals, this demand was added to the district heating demand. Hence, the total demand in the two 2030 scenarios is the same, but the coal consumption differs.

All the thermal efficiencies corresponding to the technologies are based on the values considered in the Decarbonised scenario.

Concerning the individual heat demand distribution and the district heating demand distribution, it was considered the ones in the BL and scenario, coloured as grey in Figure A.3.

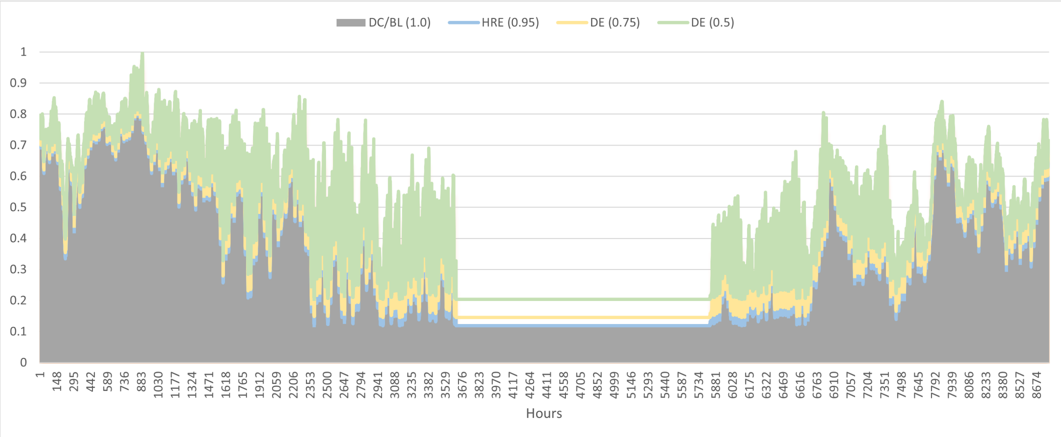

Figure A.2: District heating demand distributions. Own elaboration.

The analysis contains several DH demand distributions as represented in the figure, which can access different consumption behaviours. The demand per building is considered to be 15000 kWh/year, and a lower value would mean an increase in buildings' energy efficiency.

Cooling sector

Table A.4: Cooling sector. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**
Individual (TWh/year)	6.31	112.78	112.78	51.94	51.94
District Cooling (TWh/year)	0.00	0.00	0.00	0.00	0.00

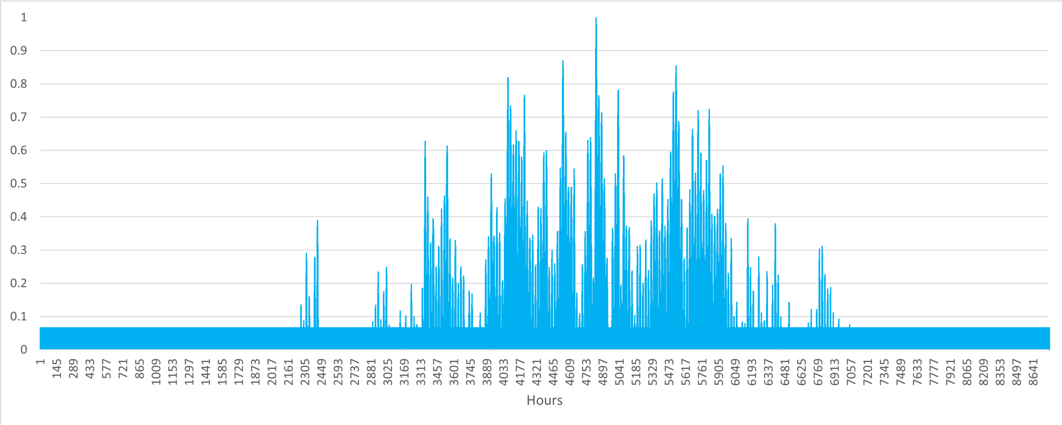

Figure A.3: Cooling demand distribution. Own elaboration.

Industry sector

Table A.5: Industry sector. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**
Coal (TWh/year)	168.10	137.88	12.46	155.15	0.00
Oil (TWh/year)	42.96	17.64	91.70	32.11	63.85
Natural gas (TWh/year)	323.80	155.35	20.61	251.61	193.86
Biomass (TWh/year)	53.07	93.66	89.80	70.47	68.81
Hydrogen (TWh/year)	0.00	0.00	213.31	0.00	192.82

Similarly to the heating sector, with the resource of a linear interpolation, the Decarbonised scenario in 2030 would have coal consumption since 2050 considered its use. However, this behaviour is not alignment and the coal consumption of 101.40 TWh/year is added to the hydrogen demand.

Moreover, the demand distribution in Industry is considered as constant.

Transportation sector

Table A.6: Transportation demand. Own elaboration.

	Baseline (2015)	Baseline (2050)	Decarbonised (2050)	**Baseline (2030)**	**Decarbonised (2030)**
Jet fuel (TWh/year)					
Fossil	101.56	182.76	52.60	136.36	80.57
Biofuel	0.00	0.00	18.92	0.00	8.11
Electrofuels	0.00	3.43	77.33	1.47	33.14
Diesel (TWh/year)					
Fossil	337.63	194.99	4.20	276.50	194.73
Biofuel	26.03	5.40	16.20	17.19	21.81
Electrofuels	0.00	0.00	0.00	0.00	0.00
Petrol (TWh/year)					
Fossil	213.59	55.17	6.13	145.70	124.68
Biofuel	5.39	2.98	23.11	4.36	12.99
Electrofuels	0.00	0.00	0.00	0.00	0.00
Natural gas (TWh/year)	2.68	0.61	30.22	1.80	14.49
LPG (TWh/year)	6.09	0.06	0.61	3.51	3.74
Ammonia (TWh/year)	0.00	0.00	0.00	0.00	0.00
Hydrogen (TWh/year)	0.00	0.00	84.38	0.00	36.16
Electricity (TWh/year)	17.51	125.17	122.12	63.65	62.34

Electrical vehicles (EVs) in the EnergyPLAN are divided into dump and smart cars. The dump cars will be considered for the base scenarios, meaning that the transportation demand will be reflected using an annual demand and distribution curve. The distribution curve of the transportation demand is critical, more concretely in the EV and fuel cell electric vehicles (FCEVs) case, where it substantially impacts the power sector. The demand curve for both vehicles considered is seen in Figure A.4.

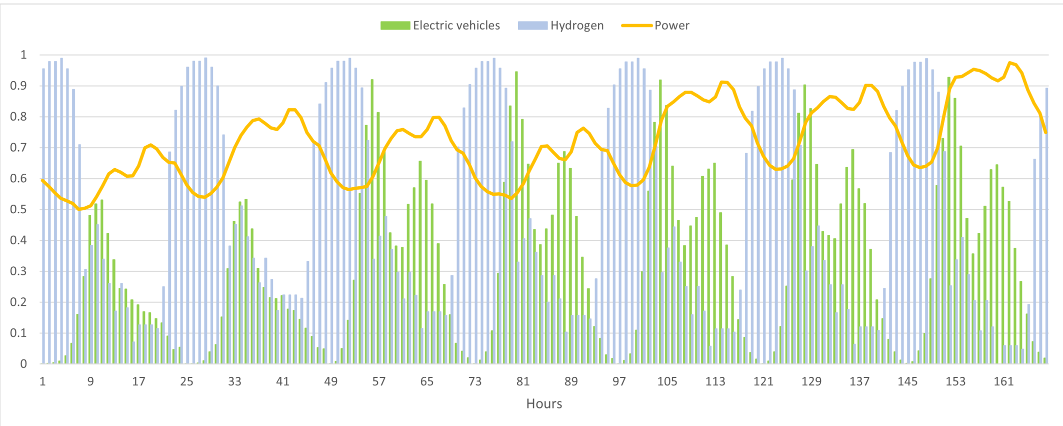

Figure A.4: Transportation demand distributions. Own elaboration.

As seen in the figure, it is possible to note that EV demand follows the power demand to some extent. Nearly opposite to the hydrogen demand mainly focused between 11 pm and 6 am.

The water demand will be disregarded since it is not accounted for in any scenario.