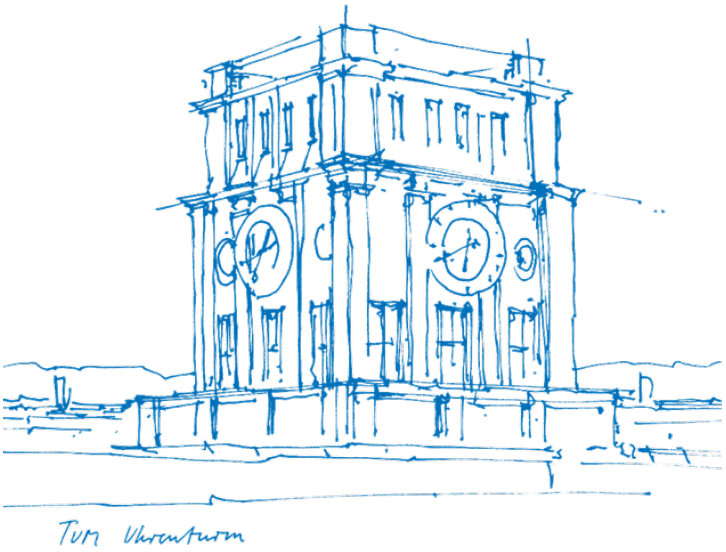
Chair of Renewable and Sustainable Energy Systems
TUM School of Engineering and Design
Technical University of Munich

Master's Thesis

Future-oriented Life Cycle Assessment of the Energy System Considering the Deployment of Bidirectional Charging Strategies

Sarah Schmidt



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Future-oriented Life Cycle Assessment of the Energy System Considering the Deployment of Bidirectional Charging Strategies

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I hereby declare that this thesis is entirely the result of my own work except where otherwise indicated. I have only used the resources given in the list of references. I have not previously submitted this thesis for academic credit.

Munich, 16.10.2023

Sarah Schmidt

Abstract

Vehicle-to-grid is an emerging technology enabling flexibility in energy systems through the dual use of electric vehicle batteries: on the one side to store energy for vehicle propulsion and on the other side to provide short-term storage capacity in the energy system. Deploying such bidirectional charging strategies on a large scale in the future endogenously influences the expansion of the energy system and, by extension, its consequences on the environment. The purpose of this thesis is to evaluate the prospective life cycle impacts of the difference in the overall German energy supply sector expansion induced by this flexibility option until 2050.

To characterize the difference, an inventory of the divergences in power plant construction and primary energy carrier consumption required for meeting the future energy demand is established. This is done by confronting energy system scenarios relying on the same assumptions and whose only difference lies in the ability of the available battery electric vehicle fleet to perform bidirectional charging. The major difference in endogenous energy system expansion accountable to vehicle-to-grid services resides in the avoidance of stationary 1st and 2nd battery energy storage systems manufacture. Both are subject to high greenhouse gas emissions and critical metal resource utilization. On the other hand, vehicle-to-grid requires the supplementary fabrication of information and communication technologies for electric vehicle charging infrastructure. Other energy system changes are marginal in relation to the overall energy system expansion and are majorly ascribable to the energy system model cost optimization.

Over the entire time frame, a total of 14.9 Mt CO_2-eq and 41.1 Mt Fe-eq may be saved by introducing vehicle-to-grid technologies in the German energy system. Savings in global warming potential, thus, remain marginal with respect to current levels, while the deployment of bidirectional charging strategies may confer a noticeable advantage in metal resource preservation attributable to the lesser need for stationary battery systems. Elaborated results are, however, decidedly subject to assumptions and model results due to the marginal divergences in energy system expansion brought forth by the flexibility option on the whole. A sensitivity analysis of the emission factor assigned to the manufacture of 1st life battery packs shows that for smaller values, the potential decrease in greenhouse gas emissions might be even less significant on a global scale.

The realization of the prospective life cycle assessment has been conducted by conceiving an automated framework evaluating the difference in environmental impacts on the energy system expansion induced by any given measure, technology, or policy. The thesis, accordingly, also accounts for the methodology set in place for the conception of such a framework.

Keywords – vehicle-to-grid, prospective life cycle assessment, energy system model, global warming potential, metal depletion, automated framework

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List of Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage Systems
BEV	Battery Electric Vehicle
DB	Database
DC	Direct Current
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
EMF	Emission Factor
ESM	Energy System Model
EU	European Union (EU 27 refers to the 27 member states of the EU)
EV	Electric Vehicle
FEC	Final Energy Consumption
FfE	Forschungsstelle für Energiewirtschaft e. V.
FREM	FfE Regionalized Energy system Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
IAM	Integrated Assessment Model
ICEV	Internal Combustion Engine Vehicle
ICT	Information and Communication Technologies
IPCC	Intergovernmental Panel on Climate Change
ISAaR	Integrated Simulation Model for Plant Deployment and Expansion Planning with Regionalization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
MDP	Metal Depletion
mME	Modern Metering Device
pLCA	Prospective Life Cycle Assessment
pLCI	Prospective Life Cycle Inventory
PV	Photovoltaic
RCP	Representative Concentration Pathway
RE	Renewable Energies
RES	Renewable Energy Sources
SMGW	Smart Meter Gateway
SQL	Structured Query Language
SSP	Shared Socioeconomic Pathway
V1G	Unidirectional Controlled Charging
V2G	Vehicle-to-Grid

1 Introduction

This thesis was written at the Chair of Renewable and Sustainable Energy Systems in collaboration with the external research institution Forschungsstelle für Energiewirtschaft e. V. (FfE).

Goal and structure of the chapter *This chapter aims to introduce the thesis' context and research motivation. It provides an overview of the addressed issues and a first insight into the applied methodology. As to the organization of the chapter, we will first provide the reader with a general motivation on the topic, from which we will elaborate the problem statement and associated research gap. From this, we will be able to formulate the objectives and research questions dealt with within the framework of the thesis. We will conclude the chapter with an outline of the thesis' structure.*

1.1 Motivation

Human activities and the thus magnified greenhouse gas (GHG) emissions have irrefutably caused global warming and have already induced global surface temperature rises of 1.1 °C above their level in 1850-1900 (IPCC, 2023). On a world scale, the IPCC estimates in their latest assessment that the energy supply sector has issued 13 Gt CO_2-eq[1] in 2019, which represents 23% of the overall GHG emissions in that year, and places it as the second most polluting sector right after the industry sector at 24%. On an EU 27 level, its part even reaches 27% in 2021 (European Environment Agency, 2023) ranking it as the number one most polluting sector. Facing the most apparent need to drastically reduce the GHG emissions of the electricity and heat supply, a clean energy transition features at the core of the EU's target of reducing their GHG net emissions to zero by 2050 within the scope of the European Green Deal (European Commission, 2019). The German government places renewable energies (RE) as a central measure for reaching carbon neutrality on that year; by 2050 the German energy consumption shall be covered by 60% from renewable energy sources (RES), the electricity consumption shall even be sustained by 80% from RES (BMWi, BMU, 2010). As a means of guaranteeing a successful integration of RE, the Federal Ministry for Economic Affairs and Climate Action identifies in its energy concept (BMWi, BMU, 2010) the development and promotion of storage technologies as being a key aspect and challenge of the expansion of RE.

Indeed, storage devices are a particularly contemplated option for counteracting the fluctuating availability of RES – especially wind and photovoltaics (PV) – in an energy system with a high share of such energy sources. Weitemeyer et al. (2015) highlight the necessity of finding a compromise between installing additional generation capacities and storage technologies in a system in which over 50% of the electricity demand is met by RES. More importantly, they found that small, short-term storage devices with high efficiency are more beneficial in terms of RES integration for such a system, while less efficient seasonal storage technologies only come in handy for a system with a coverage of the electricity generation by RES of over 80%. By fitting the short-term storage criteria, battery energy storage systems (BESS) manifest themselves as being a fast, flexible, and reliable means for providing active power and performing peak shaving (Datta et al., 2021; Koller et al., 2015); yet they come with a number of downsides, notably a low lifetime and a high economical and environmental cost. Concerning the latter, batteries need a vast and various amount of raw metal and non-metal materials during their production process and generate

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[1] CO_2-eq stands for carbon dioxide equivalent, which is a measure for assessing and comparing the global warming potential (GWP) of all GHG. In the framework of this thesis, emissions are converted to their corresponding CO_2 equivalent considering a 100-year GWP (GWP 100).

a considerable amount of environmental pollutants, e. g. GHG, toxic gases, and hazardous waste, at all stages of their lifetime (Dehghani-Sanij et al., 2019).

At the same time, batteries also play a very important role in the decarbonization of the transport sector and, more specifically, the automotive industry, as battery electric vehicles (BEVs) are starting to be deployed as a substitute for internal combustion engine vehicles (ICEVs). In Germany, approximately 19% of the total GHG emissions (146 Mt CO_2-eq) stemmed from the transport sector in 2017, 80% of it being issued by motorized private transport, like passenger cars and motorcycles (Schelewsky et al., 2020). Yet, at odds with the German and European climate targets (BMWi, BMU, 2010; European Commission, 2019), the number of passenger cars keeps steadily increasing (48 million passenger cars in 2023 compared to 30 million in 1990 (Kraftfahrt-Bundesamt, 2023)), as does the number of traveled passenger-kilometers. Despite the beginning of electric vehicle (EV) commercialization a decade ago, over 90% of all registered cars in Germany are still powered by fossil fuels, mainly by gasoline or diesel (Kraftfahrt-Bundesamt, 2023). However, the trend of new registrations tends in favor of EVs: in May 2023, almost 40% of all new registrations in Germany had an electric drive, and 50% of those were BEVs. From 2035, the sale of new petrol and diesel cars will be banned in the EU (European Parliament, 2023), with the intention of establishing EVs as the core of the automotive market.

BEVs have the potential of substantially reducing the global warming potential (GWP) of the transportation sector by preventing GHG emissions caused by fuel consumption (Bieker, 2021). On the other side, this benefit is mitigated by the high battery cell production (Ellingsen et al., 2016) and the electricity production impacts, which are particularly dependent on the energy carrier. For the sake of example, according to Bieker (2021), the life cycle GHG emissions per kilometer of BEVs in India are close to those of ICEVs, while in Europe, BEVs are clearly less polluting than their conventional counterpart. This is attributable to the fact that fossil energy sources have a much higher weight in the Indian electricity mix than in Europe. Yet, even within a country, the proportion of fossil energy might show large fluctuations based on the time of day and resource availability. Especially in a country with a high share of RES-based electricity production, such as Germany, the carbon footprint associated with electricity generation depends on the disposal of those sources. Considering e. g. the day-night cycle of PV presence, charging by night is linked with higher emissions than charging by day (Arvesen et al., 2021; Nunes et al., 2015). Fattler and Regett (2022) showed that smart controlled emission-optimized charging could have permitted a GWP reduction per driven kilometer of 15% in 2020 in Germany. Such peak shaving associated with an intelligent charging measure further allows to reduce the GWP of the energy system in itself (Jochem et al., 2015).

Taking the idea of optimized charging further and combining it with our previously identified need to provide fast, short-term storage in an energy system with a high share of RES, batteries already present in BEVs might act as a mobile and flexible storage option in the overall energy system, thus permitting a twofold use of the storage capacity of BEVs. Bidirectional charging is an emerging technology that allows BEVs to not only receive power from the grid but also to supply it back to it. The faculty of a BEV to feed electricity back into the grid, in addition to its standard operating mode, and hence to perform bidirectional charging, is called vehicle-to-grid (V2G). As a consequence, BEVs would not only be passive energy consumers with a high load profile but also active energy storage systems; electricity stored in the BEV at times with a high share of RES in the electricity mix can be discharged and used as a replacement for fossil energy sources at times when RES are not prevailing in the energy system. Despite the concept of V2G having already been introduced in the late 20^{th} century by Kempton and Letendre (1997) and its technical feasibility demonstrated for single EVs a few years later by Brooks et al. (2002), it has not been deployed on a wide scale yet, and remains at a pilot stage (Lauinger et al., 2017).

The main interest of V2G lies in its dual battery usage, from which follows a dual perspective on the technology: the automotive perspective and the energy system perspective. As such, it helps in jointly counteracting some previously singled-out battery downsides from each point of view. Especially from an energy system's perspective, V2G enables to avoid the manufacturing of supplementary costly and polluting stationary BESS; BEV batteries then fully take in the role of the BESS and all its benefits on the electricity grid i. e. contributing to grid stability, facilitating the integration of RES and performing peak shaving (Child et al., 2018; White and Zhang, 2011), which ultimately leads to reducing the cost of electricity as well as of BEV ownership (Schuller et al., 2014). Focusing above all on the environmental challenges of the energy and transport sectors, Xu et al. (2020a) showed that V2G could reduce the electricity production's GWP by 17% compared to a system without controlled charging and 11% compared to one with smart charging; a decline can even be observed in relation to a system without any BEVs and incurring additional load. Closing the loop, the drop in the electricity mix' GWP directly affects the BEVs' GWP as highlighted by Fattler (2021).

As it is, bidirectional charging only constitutes one in multiple options for future BESS and is not the only possible use case for BEV batteries. Indeed, going back to the idea of deploying stationary battery systems, BEV batteries could be extracted and repurposed for usage in stationary battery packs at an early stage of their life span, thus extending their lifetime and likewise to V2G, avoiding the need for manufacturing new battery packs (Casals et al., 2019). Such reused batteries will in the following be referred to as 2^{nd} life batteries, as opposed to 1^{st} life batteries being their non-recycled equivalent in stationary BESS. The remanufacturing of battery cells having a much lower GWP than the original manufacturing of the cell (Ahmadi et al., 2017; Philippot et al., 2022), the environmental advantage of EV battery repurposing stands in direct concurrence with bidirectional charging strategies.

In the face of the climate challenge ahead, this thesis aims to provide a more comprehensive view of the ecological repercussions induced by deploying bidirectional charging strategies in the years to come on a global energy system scale and viewpoint. We thereby hypothesize that having BESS in the future energy system is inevitable and that its provision could be fulfilled by 1^{st} life batteries, 2^{nd} life batteries, and/or V2G services. Our goal is to assess the life cycle environmental impacts of the needed power plant park expansion brought forth by spreading out V2G as a BESS technology option in addition to stationary battery systems. For this purpose, we will confront an energy system scenario featuring the V2G option to one where this technology is not deployed.

1.2 Literature Review and Research Gap

We now proceed with a literature review in order to identify the research gap leading to the problem addressed in this thesis. Classifying literature on the environmental impacts of bidirectional charging strategies, studies on this topic should be differentiated as per the following aspects:

1. The perspective – as previously highlighted, based on the dual use of the stored electricity, V2G can be considered either from the automotive or the energy system's point of view.
2. The application domain – bidirectional charging strategies can be deployed on a wide-ranging as well as on a local grid scale. Wide-ranging applications commonly include countries or region-wide electricity grid systems, while local applications might confine the grid to a particular building or area.
3. The comparison technologies – inferences on the environmental impacts of the V2G technology are typically compared with other related technologies. For the most part, such technologies can be other charging strategies, e. g. uncontrolled and smart charging, or replacement technologies like diesel generators or stationary batteries.
4. The environmental impact assessment methodology – life cycle assessment (LCA) has established itself as a popular assessment method due to its thorough accounting of impacts throughout the entire lifetime of the considered system; nevertheless, other approaches can still be considered.
5. The time frame of the assessment – the analysis might take place nowadays or in the future. Moreover, it might be based on current technological standings and emission factors (EMF) or make assumptions on their future progression. An assessment process for which such future-oriented assumptions are made will further be qualified as prospective.

Going back to the first criterion, this thesis takes the energy system point of view as opposed to the automotive perspective, whence the upcoming literature review focuses on this viewpoint. It shall further be said that any drawn conclusions within the framework of this thesis will be reached from this perspective only and would further need to be weighed against the advantages and drawbacks of other viewpoints. Now, building upon the remainder of the criteria given above, we list the specifications of reviewed studies in Table 1.1 in order to highlight their characteristic features and outline gaps in the state of the art.

Authors	Title	Scale	Comparison	Assessment method	Time frame
Ali et al. (2020)	“Economic and Environmental Impact of Vehicle-to-Grid (V2G) Integration in an Intermittent Utility Grid”	LUMS university	diesel generator peak shaving	direct emissions	2017, not prospective
Blasuttigh et al. (2023)	“Vehicle-to-ski: A V2G optimization-based cost and environmental analysis for a ski resort”	ski resort in Italy	uncontrolled charging, V1G[a]	direct emissions	2023 and 2030, not prospective
Regett et al. (2019)	“Using Energy System Modelling Results for Assessing the Emission Effect of Vehicle-to-Grid for Peak Shaving”	office building in Germany	without peak shaving, diesel generator peak shaving	LCA	work day in 2030, not prospective
Sioshansi and Denholm (2009)	“Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services”	Texas	diesel generator peak shaving	direct and upstream emissions	2005, not prospective
Wang et al. (2022)	“Integrating vehicle-to-grid technology into energy system models: Novel methods and their impact on greenhouse gas emissions”	fictive country akin to Germany	uncontrolled charging	LCA	2050, not prospective
Xu et al. (2020a)	“Greenhouse gas emissions of electric vehicles in Europe considering different charging strategies”	Europe	without EVs, uncontrolled charging, V1G	LCA	up to 2050, prospective
Yao et al. (2022)	“Economic and climate benefits of vehicle-to-grid for low-carbon transitions of power systems: A case study of China’s 2030 renewable energy target”	China	V1G	direct emissions	2030, not prospective
Zhao and Baker (2022)	“Effects on environmental impacts of introducing electric vehicle batteries as storage-A case study of the United Kingdom”	UK	battery swapping, 1st life batteries, 2nd life batteries	LCA	2050, not prospective

Table 1.1 Literature review on the environmental impacts of bidirectional charging strategies taking on an energy system’s perspective

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[a] V1G refers to unidirectional controlled charging and can thus be affiliated to smart charging.

Bidirectional charging being a driver towards a decentralized provision of battery storage, multiple studies present results on a microgrid scale; it is worth mentioning the diversity in the analyzed microgrids, among which we have identified a university campus (Ali et al., 2020), an office building (Regett et al., 2019) and a ski resort (Blasuttigh et al., 2023). On such a local range, the provision of stored energy in the context of peak shaving is often ensured by a diesel generator with high CO_2 emissions. Replacing peak shaving by such an environmentally unfriendly backup source with V2G storage services on a microgrid scale would lead to a 6% CO_2 emissions reduction in the German office building (Regett et al., 2019) and even to a 25% reduction in the intermittent grid of LUMS university (Ali et al., 2020). Increasing the scope of the V2G application to an entire region, Sioshansi and Denholm (2009) assessed that V2G could counterbalance up to 80% of the increase of generator CO_2 emissions needed by introducing a plug-in hybrid EV fleet on the Texan grid load. Due to the different scopes, charging profiles, vehicle characteristics, etc., involved in these studies, the just-mentioned saving potentials are not comparable.

Should the operation of a diesel generator for peak shaving purposes not be necessary, V2G can nevertheless be employed for storage purposes, reducing the amount of energy drawn from the grid and favoring charging at off-peak hours and/or low-emission times depending on the applied charging strategy. Taking on the point of view of a local facility, a substantial part of the required energy can be self-sustained by V2G services (about 6.5% in the application of V2G in an Italian ski resort (Blasuttigh et al., 2023)), consequently and proportionally reducing the carbon footprint associated with drawing energy from the grid. Bidirectional charging strategies can even lessen the GHG emissions of the energy system in itself, especially in a system with a high share of RE, where the need and benefits of the provision of storage capacity are highest (Wang et al., 2022). Along these lines, Yao et al. (2022) found that in a coal-heavy generation system such as China, as opposed to a RES-based electricity production, unidirectional smart charging might even induce a slightly more important reduction of CO_2 emissions in the power system than bidirectional charging, thus outweighing the storage benefits of V2G.

Further than that, spreading out bidirectional charging strategies endogenously influences the requisite expansion of power plant facilities. Thereby, in their study, Xu et al. (2020a) couple the output of an energy system model's (ESM) future electricity mix, which incorporates a bidirectional charging policy, with the realization of a pLCA (prospective LCA), thus estimating the prospective life cycle GHG emissions of the electricity production bound to deploying V2G technologies. They confront their results with different charging technologies, in particular uncontrolled and unidirectional charging, finding that V2G might save over 10% of the overall electricity system's GHG emissions in both cases; yet they do not consider replacement technologies for the provision of storage by BEVs should V2G services not be deployed, which in the face of the expansion of fluctuating RES-based electricity generation is unlikely (Wali et al., 2021; Weitemeyer et al., 2015). Tackling this issue, Zhao and Baker (2022) assert the delivered electricity's life cycle impacts opposing different BESS provision options, notably 1^{st} life batteries, 2^{nd} life batteries, and mobile BEV storage. They even find a decrease in the GWP of the electricity mix when stationary batteries are prevailing in the system in contrast to V2G technologies; the decrease is accentuated in the case 2^{nd} life batteries are the prominent BESS technology as opposed to 1^{st} life batteries. However, their study does not consider prospective EMF for the calculation of the system's environmental impacts, nor does it account for the endogenous construction of supplementary power plant facilities.

Therefore, this thesis aims to fill the gap in research on the forward-looking environmental impacts of the deployment of a bidirectional charging flexibility option on an overall energy system's scale. Thereby, the following issues are being addressed within the scope of the thesis:

1. We include the provision of all energy carriers in the system within the scope of the assessment, hence going beyond mere electricity production.
2. We use an integrated future ESM, taking into account the alternative provision of BESS (in the form of stationary 1^{st} and 2^{nd} life batteries) in the case V2G services are not spread out. Besides, the model delivers endogenous energy system results in both cases, thus featuring the different needed power plant parks for energy generation.
3. We focus on the provision of installed capacities, assessing the constructed power plant facilities needed for meeting the energy demand brought forth by the deployment of V2G policies. For the

sake of completeness, the required input and combustion of primary energy carriers for the endogenous operation of the power plant park shall also be considered.

4. We perform a pLCA on the overall energy system expansion's life cycle, considering a time frame of five-year steps starting in 2025 and ending in 2050.

The pLCA performed during this thesis shall be carried out on the difference in the overall future energy system induced by the supplementary deployment of a bidirectional charging flexibility option, hence opposing two instances of power plant park expansion – one in the case storage capacity is provided by stationary batteries only, and one in the case BEVs can additionally be used for storage within a V2G deployment policy. Therefore, a differential point of view is conducted for calculations throughout this thesis as opposed to an absolute one; this will also be valid for any deductions drawn within the scope of the thesis. As it is, the difference in the power plant park expansion will be evaluated considering the construction and operation of facilities, setting aside their end-of-life, and the associated disposal and recycling of materials. Furthermore, the pLCA is to be realized on the difference in the German power plant park, ergo a country with a high expansion and share of RE and consequently a substantial need for BESS.

1.3 Objectives and Research Questions

On a superordinate level, the thesis' purpose is to evaluate the auxiliary environmental impacts of the energy system induced by introducing the flexibility option "bidirectional charging" by performing a future-oriented LCA, i. e. a pLCA, on it. By doing so, particular attention shall be paid to the previously identified research gaps. More precisely, the thesis seeks to ascertain if bidirectional charging strategies constitute an environmental advantage in the future on an energy system's scale, especially when considering the entire life cycle of the installed power plant fleet. We can thus formulate two major subordinate objectives for this thesis: one is related to the technical realization of the assessment, and the other to the actual application of bidirectional charging. Three research questions can further be derived from the sub-objectives to act as a guideline for this thesis.

As part of the first subsidiary objective of this thesis, a framework shall be developed for the automated realization of a pLCA on the overall energy system's difference induced by a given measure. The difference can be determined by considering two forward-looking energy system scenarios – one implementing the measure at hand and the other representing a base scenario without integration of the measure. The scenarios serving as the framework's basis are to be taken from the ESM ISAaR; the framework should then be able to retrieve the ISAaR scenario results and conduct a pLCA based on the capacities contributing to the overall energy system difference. Particular attention shall be given to the construction and dismantling of power plant facilities, whereas the power plant's use phase shall be evaluated based on their primary energy carrier combustion. Moreover, the implemented framework is to be applicable to any technology choice or policy evaluated in ISAaR. This first objective can be transcribed into a research question.

Research question 1 How can the prospective life cycle assessment on the difference in the overall energy system expansion induced by the future deployment of a given measure be realized in an automated way?

As a practical application of the tool and in order to comply with the superordinate objective of the thesis, an ISAaR scenario featuring bidirectional charging strategies and one which does not are to be used within the framework, thus assessing the environmental impacts of such a flexibility option. An interpretation of the results will allow us to conclude within the framework's hypotheses and boundaries on potential ecological advantages or disadvantages of the V2G technology as part of the thesis' main objective, as recorded in the second research question. Different evaluated impact categories might lead to different conclusions.

Research question 2 In the future, will there be an environmental advantage from the energy system's perspective to using mobile EV storage by spreading out bidirectional charging over using alternative battery storage?

We shall further identify particularly environmentally harmful or beneficial energy system expansion processes as part of the result interpretation and comparison of the two scenarios. This identification will further be put into perspective with respect to the chosen relevant impact categories and is reflected in research question 3, which constitutes a subsidiary objective to research question 2.

Research question 3 Which additionally built facilities within the deployment of the flexibility option "bidirectional charging" have particularly high environmental impacts? Which impacts can be saved by introducing this measure?

1.4 Organization of the Thesis

For the fulfillment of the objectives laid down in the previously stated research questions, the thesis will be structured as follows. First, Chapter 2 provides the reader with the theoretical background and relevant notions related and incumbent for the accomplishment of the set goals in the rest of the thesis. The devised methodology for the conception of the automated framework will be presented in Chapter 3. Its application to the evaluation of bidirectional charging strategies' environmental impacts is conducted in Chapter 4. Finally, Chapter 5 concludes this thesis by giving the main drawn inferences, the limitations of the realized work, and some suggestions for future research pathways.

Chapter summary *In this chapter, we have presented bidirectional charging strategies as being a thinkable pathway towards a dual usage of BEV batteries: one for providing electricity storage for the vehicle propulsion and one for providing short-term storage capacity in the energy system. Filling in the identified gap in research, this thesis aims to conduct a pLCA for assessing the environmental impacts on the overall energy system induced by deploying such a flexibility option. Particularly, we will be accounting for the endogenous energy system expansion difference required by introducing V2G technologies in addition to stationary BESS. For this purpose, a framework for the automated pLCA of the energy system impacts of a given flexibility option or policy is to be conceived and applied to the case of bidirectional charging.*

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2 Theoretical Background

This thesis relies on a number of scientific concepts and software environments for its realization. Some have already been cited in the portrayal of our objectives in Section 1.3: pLCA, prospective EMF, ESM, ISAaR, ... Some others have not been mentioned yet but are essential to the resolution of our problem at hand nonetheless: ecoinvent, *premise*, integrated assessment model, FREM, ... In order to clarify each of these notions and concepts to the reader and thus make sure to lay down a common ground for the comprehension of this thesis, we will be going over the theoretical background related to each one of them in the oncoming chapter.

Goal and structure of the chapter *This chapter provides the reader with the necessary knowledge and background for fully grasping the remainder and core of the thesis. In order to do so, we will be introducing the theoretical concepts as well as the software environments on which we will rely during the conception and realization of our own framework. The chapter's structure is organized around the coupling between environmental assessment and ESM results. Thereby, we will first present the pLCA methodology and, afterward, give insights on energy system modeling as a tool for estimating future energy system states, with special attention to the combination of both frameworks.*

2.1 The Prospective Life Cycle Assessment Framework

The pLCA methodology constitutes the main pillar of this thesis around which revolves the step-by-step conception of our framework. It is a future-oriented mode of the "classical" LCA framework, specialized in the estimation of a product's future environmental impacts using forward-looking scenarios (Guinée et al., 2018). Its realization follows the same stages as a "classical" LCA, whence we deem it relevant to present them in the following.

2.1.1 General Principle of Life Cycle Assessment

The European Commission's Joint Research Centre and Institute for Environment and Sustainability (2010) introduces LCA as a:

> *"structured, comprehensive and internationally standardized method [that] quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services."*

In other words, LCA is a methodology for the evaluation of a multitude of environmental impacts of a chosen product, function, or service, considering its entire life cycle impact contributions. The particularity of LCA is to provide quantitative indicators on the different studied impacts for each life stage of the object of study, including but not limited to its raw material extraction, manufacture, distribution, use stage, disposal, and recycling. The LCA method has been documented and regulated in the ISO 14040:2006 and ISO 14044:2006 standards (International Organization for Standardization, 2006a,b); we will conduct this thesis' LCA in conformity with them.

The LCA framework is broken down into four steps, each and every one crucial to a proper LCA implementation: in the correct procedure order, the goal and scope definition, the life cycle inventory analysis, the life cycle impact assessment (LCIA), and an interpretation. It is important to note that these stages are not considered as a list to tick off step-by-step but should be assimilated into an intricately interconnected workflow, where each phase is constantly revised and adapted with every new insight (Hauschild et al.,

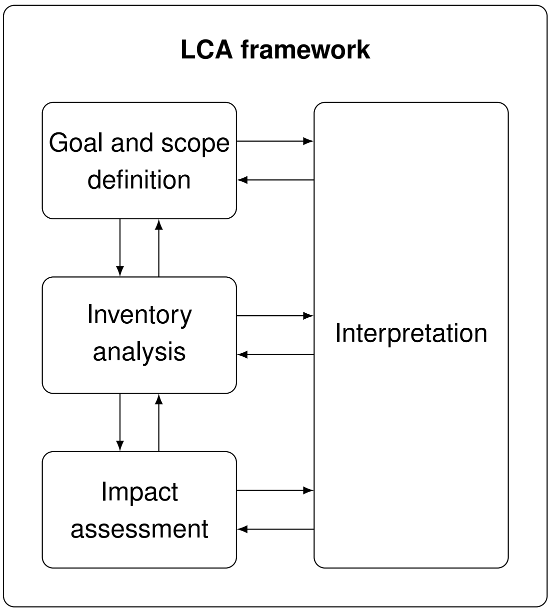

Figure 2.1 Principle of LCA framework according to ISO 14040:2006 (International Organization for Standardization, 2006a)

2018). Figure 2.1 illustrates the four steps of the LCA framework as well as their interconnections. We will now proceed with a more detailed explanation of what each stage consists of.

Goal and scope definition This first phase's primary objective is to set the why – the goal – and the what – the scope – of the LCA. The goal is relative to the LCA's purpose and settles its context, intended result applications, and limitations (Hauschild et al., 2018). The scope lays down several key factors and criteria on the system – i. e. product, function, or service to be studied – which govern the practical realization of the LCA in the next steps.

Foremost, the LCA practitioner needs to define the function, functional unit, and boundaries of the system. The function specifies the use to which we want to put our system, e. g. if we want to study a car, we might be interested in analyzing the impacts of transporting people and goods or of producing the car in itself; they represent two different functions of a same studied system. The functional unit provides a reference unit for expressing the impact results of the analysis and relating the input and output flows composing the system. Returning to our previous example, the impact of transporting people and goods would be given with respect to one passenger-kilometer or one vehicle-kilometer and the impact of producing a car with respect to one manufactured car. The system boundaries set the limit and the extent to which we assert the system at hand; they include the system flows to take into account, the spatio-temporal scope of the LCA, and the life phases to be examined. Introducing some terminology on the latter, the life cycle of a product can be broken down into different stages, from the extraction of raw materials, i. e. the cradle, to the disposal and recycling process upon a product's end-of-life, i. e. the grave. We would then call "cradle-to-grave" a system boundary considering all these life stages. This terminology is further illustrated and complemented by the life stage "gate" in Figure 2.2. Within the scope definition, the LCA practitioner also settles which impact categories[1] to assess, which allocation procedure[2] to employ, and some other aspects bound to the interpretation phase of the LCA.

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[1] An impact category is a category representing one important environmental issue. Some common ones include climate change, resource depletion, or eutrophication.

[2] We refer to allocation when we want to estimate the environmental impact of individual products yielded by multifunctional systems, i. e. systems which produce more than one product; the "environmental responsibility" of the process then has to be shared among the co-products. Whenever possible, allocation should, however, be avoided.

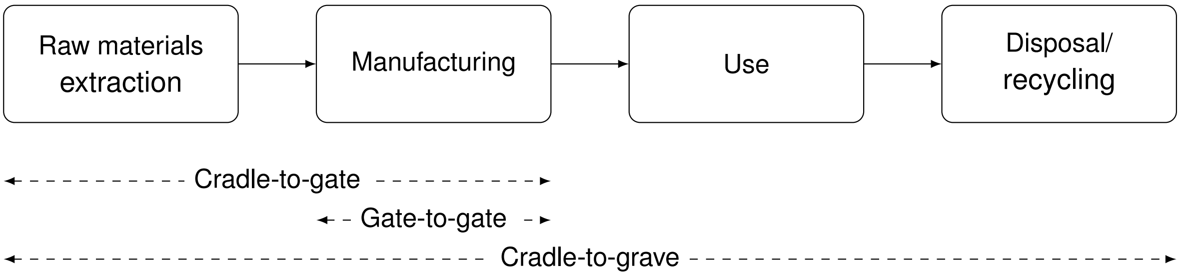

Figure 2.2 Life phases of a product and associated system boundary terminology adapted from Simonen (2014)

Inventory analysis The goal of this step is to associate the different unit processes[3] composing the system through material and energy flows. Indeed, it is possible to connect each unit process within the system boundaries to the other unit processes via its input flows, i. e. its material, energy, and resource needs, and its output flows, i. e. its product, emission, and waste generation (see Figure 2.3). All unit processes are to be related and aggregated with respect to the system's functional unit and reference flows for coherent data validation. Gathering information on the flow values probably represents the most challenging part of the LCA framework, as primary data is often difficult to access. Under primary data, we understand product data directly measured or published by the company, as opposed to secondary data often obtained through databases (DBs) that centralize generic process information; the ISO standard advocates the use of primary data over secondary data. Allocation is also performed within the inventory analysis step. The result of the inventory analysis is the life cycle inventory (LCI), which takes the form of a collection of data transcribing the physical elementary process flows and amounts leading to the fulfillment of the system's function.

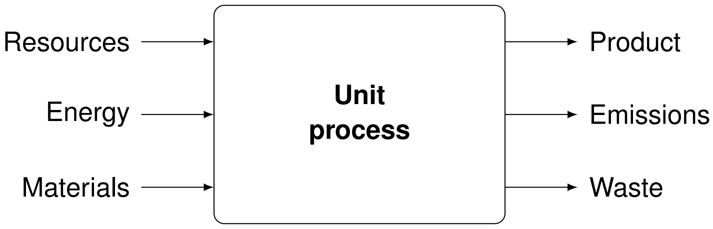

Figure 2.3 Unit process as in Hauschild et al. (2018)

Impact assessment The previously gathered elementary input and output flows are translated into indicators of their environmental burden within the LCIA. Thereby, LCI flows are assigned to the respective impact categories they contribute to and then multiplied by a (characterization) factor, which reflects their relative contribution to the category. As a result of these two steps – entitled classification and characterization – we obtain a single score for each category in a common unit, e. g. for the impact category "GWP" this unit would be CO_2-eq. Scores can be further normalized with respect to a reference value and/or weighted in order to obtain a single score across all impact categories.

Impact categories can be classified into mid- and endpoint indicators. Endpoint indicators represent an aggregation of different environmental problems, i. e. midpoint indicators; one midpoint indicator can, however, lead to different endpoint indicators. Due to their nature, endpoint indicators come with a relatively high level of uncertainty and require the use of complex models. The ReCiPe methodology (Goedkoop et al., 2009; Huijbregts et al., 2016) defines three endpoint indicators: 1) the damage to human health, 2) the damage to ecosystems, and 3) the damage to resource availability. There are, on the other hand, many more midpoint indicators. Apart from GWP, now mentioned many times, a midpoint indicator might,

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[3] A unit process can be assimilated to one or more grouped operations needed to ensure a product's function over its life cycle. For example, for producing a car, a unit process might be the production of steel required for manufacturing the chassis.

for example, be the water use required by the system, which has direct impacts on human nutrition and, therefore, on human health, as well as on the survival of species and, therefore, on ecosystems.

Interpretation The interpretation step rounds off the LCA process and suggests a stage for showcasing and analyzing the previously obtained values. Multiple complementary and non-compulsory analysis approaches are available to the LCA practitioner; his choice should be specified within the goal and scope definition. Usually, this step serves to evaluate and critically discuss results, thereby drawing the main conclusions and maybe even recommending some future pathways. A sensibility analysis is often employed to appraise the repercussions, which important assumptions, such as allocation procedures and system efficiencies and lifespans, may have on the results. Presenting the LCA outcomes to a target audience is also part of this step; it is essential to share the LCA's assumptions and limitations with the audience and, in the case of a scientific report, even the entire LCA procedure.

2.1.2 Numerical Implementation of Life Cycle Assessment

It is possible to conduct an LCA by hand or with a spreadsheet editor, yet for very detailed and intricate LCIs, this becomes too troublesome. This is why it is common to use numerical LCA software environments for the LCA inventory analysis and impact assessment steps. Such environments enable the LCA practitioner to resort to LCI DBs for assessing background processes, i. e. process flows leading up to an exploited product, and to compute LCA impact scores for different categories in an automated way. Numerical LCIA calculations are implemented using a matrix approach (Heijungs and Suh, 2002, 2006); this mathematical theory will be further explained in the following.

Let us consider the LCI in its whole; we then have $N_u \in \mathbb{N}$ different unit processes requiring in total $N_p \in \mathbb{N}$ product flows and $N_e \in \mathbb{N}$ elementary flows. We define $A \in \mathbb{R}^{N_p \times N_u}$ as being the transaction matrix, i. e. the matrix coupling the product use and output between unit processes; the term "transaction" emphasizes the economic aspect of product flows as market trades. Analogously, the intervention matrix $B \in \mathbb{R}^{N_e \times N_u}$ transcribes the elementary flows between unit processes; interventions come into play when raw planetary resources are extracted, or waste and emissions are released into nature. Now, if $d \in \mathbb{R}^{N_p \times 1}$ symbolizes the final product demand of the studied system, then $A^{-1}d$ is the supply of products for meeting this demand. More importantly, $BA^{-1}d$ is a matrix representation of the LCI.

For each impact category, it is possible to establish a characterization matrix $C \in \mathbb{R}^{1 \times N_e}$ merging all the inventory flows involved in an impact category into an equivalent score with respect to a reference unit. In other words, this matrix's purpose is to perform the characterization step of the LCIA, as hinted by its name. The impact score $h \in \mathbb{R}$ for the impact category then is the result of the following matrix formula:

$$h = CBA^{-1}d \tag{2.1}$$

This formula is the base of a vast majority of LCA software environments, and in particular, the Brightway2 framework (Mutel, 2017), which is the framework that will be used within this thesis. Brightway2 is an open-source Python library enabling a modular and custom use of the LCA calculation framework. In addition to that, the Activity Browser (Steubing et al., 2020) provides a graphical user interface to the Brightway2 framework, easing common LCA tasks such as managing projects and DBs, modeling LCIs, and analyzing LCA results. Projects and DBs can be accessed and edited simultaneously by both Brightway2 application environments (Activity Browser and direct implementation in Python), diversifying workflow by leveraging the strength of each Brightway2 library application.

As mentioned earlier, most LCA practitioners resort to an LCI DB for modeling the system's background processes. LCA software environments, among which Brightway2, enable direct incorporation of DB information in the LCIA. We will be using the commercial LCI DB ecoinvent (Frischknecht and Rebitzer, 2005; Wernet et al., 2016) to conceive our automated framework. Ecoinvent was developed by the Swiss Centre for Life Cycle Inventories and is continuously updated to add and improve process activities; we will be working with the ecoinvent 3.8 cut-off version. This DB's data structure complies with the ISO/TS 14048:2002 (International Organization for Standardization, 2002) LCI data documentation format standard. It provides nearly 20 000 well-documented generic LCI datasets, accounting for product properties and data parameters, formulas, and uncertainties.

2.1.3 Adding Prospective Considerations to the Life Cycle Assessment Framework

A crucial point of this thesis resides in the future-oriented evaluation of the energy system's environmental impacts. Hence, we have to adapt the ecological cost of processes to an estimated future state, making assumptions on upcoming technologies, efficiencies, and policies, among other developments. Such assumptions will have repercussions on the system's whole life cycle, be it, e. g., for the transport of goods, the energy consumption during manufacture and usage, or the emission of pollutants and the emerging possibility of compensating them. In other words, when making a future-oriented LCA, the impact score, or EMF, of individual process activities takes into account such prospective considerations. This is what we call a pLCA (Arvidsson et al., 2018).

premise The Python extension *premise* (PRospective EnvironMental Impact asSEssment) (Sacchi et al., 2022) was conceived in order to enable a practical adjustment of processes' EMF to reflect future considerations. It proposes a numerical approach for producing prospective ecoinvent LCI DBs based on future scenarios generated by integrated assessment models (IAMs). Concretely, the *premise* framework transforms a given baseline LCI DB to render multiple prospective LCI (pLCI) DBs, which are adapted to projections in respective years. Figure 2.4 shows the step-by-step workflow of the *premise* framework as later put to use in this thesis. The baseline ecoinvent LCI DB and the IAM prospective scenarios are enumerated as steps 1 and 2, respectively: they constitute the inputs of the framework, the first one giving the LCIs of a multitude of processes, and the latter indicating which changes to apply on the LCIs. In step 3, *premise* operates those transformations on the baseline DB; inventories are adapted, EMFs are modified, and processes are created to account for emerging technologies not yet available or employed on a large scale. This step can be done for as many IAM scenario evaluation years as desired by the user. As a result of this key step, we get a prospective ecoinvent LCI DB for each evaluated future year in step 4. The DBs take on the same appearance as the baseline DB with the additional incorporation of the *premise* modifications. Lastly, in step 5, the pLCI DBs can be employed for ordinary LCA practice in adequate software environments (in our case Brightway2), as explained beforehand in Sections 2.1.1 and 2.1.2.

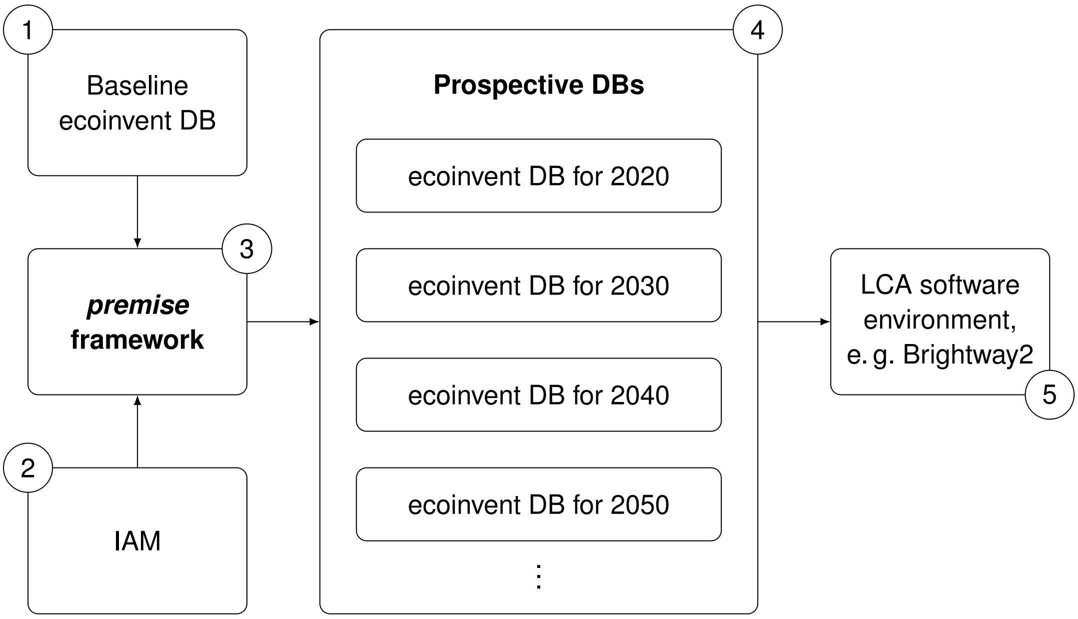

Figure 2.4 Working principle of the *premise* framework adapted from Sacchi et al. (2022)

IAM scenarios We would now like to elaborate on the repeatedly mentioned concept of IAM pathways and introduce the chosen scenario for this thesis' calculations. First, we start with the definition of an IAM as given by Hausfather (2018):

> *"IAMs are computer models that analyze a broad range of data – e. g. physical, economic, and social – to produce information that can be used to help decision-making. For climate research, specifically, IAMs are typically used to project future GHG emissions and climate impacts, and the benefits and costs of policy options that could be implemented to tackle them."*

Concretely, IAMs are used to translate a possible course of society into estimates of future energy use characteristics and its interactions with the physical climate. The scientific term "shared socioeconomic pathway (SSP)" is commonly used to refer to the demographic, societal, and economic paths the world could take. Five SSPs transcribing five very different future narratives have been developed by Riahi et al. (2017) and used in the IPCC's Sixth Assessment Report:

1. SSP1 – Sustainability (low challenges to mitigation and adaptation). In this first SSP, humanity works cooperatively to counteract climate change and gradually lead the world toward an equitable and sustainable future. Consumption is reduced and shifted towards climate-friendly alternatives, investments are made to improve health and education services and human well-being in general, and local and global inequalities are reduced.
2. SSP2 – Middle of the Road (medium challenges to mitigation and adaptation). This SSP follows historical trends. Development and growth proceed unequally across the globe, progress toward sustainable development goals remains rocky, and the fight against inequalities moves forward only slowly. All in one, efforts are made but fall short of expectations.
3. SSP3 – Regional Rivalry (high challenges to mitigation and adaptation). This SSP sees a resurgence of nationalism, coming along with a regional concern about security and competitiveness. Countries focus on internal investments and actions and refrain from international cooperation, which worsens their economic, environmental, and societal development.
4. SSP4 – Inequality (low challenges to mitigation, high challenges to adaptation). In this SSP, capital is highly unequally invested, leading to increasing economic and political influence disparities within and across countries. The gap widens between technologically advanced, capital-intensive societies and poorer, labor-intensive populations; tensions and conflicts become common as social cohesion degrades. Environmental actions are mainly taken locally in high-income areas.
5. SSP5 – Fossil-fueled Development (high challenges to mitigation, low challenges to adaptation). Lastly, this SSP transcribes a desire for rapid societal, technological, and economic progress at a world scale. The high level of investment is accomplished by an intensive development of competitive markets, an abundant exploitation of fossil resources, and the adoption of energy-heavy lifestyles. Local environmental problems are successfully tackled thanks to strong technological and scientific advances.

SSPs are usually combined with climate mitigation pathways for atmospheric GHG concentrations in 2100, which, ultimately, serves as a reference for the amount of global warming that may occur up to the end of this century. These pathways are referred to as representative concentration pathways (RCPs), and are given as a radiative forcing[4] value. Together, SSPs and RCPs form a complementary way to set the stage for the achievement – or not – of emission reductions and targets. Four RCPs have been developed by Van Vuuren et al. (2011a), spanning a range from 2.6 to 8.5 W/m^2. The RCP2.6 mitigation pathway, in particular, was conceived to explore the possibility of keeping global surface temperatures under 2 °C (Van Vuuren et al., 2011b). This pathway has been shown to be technically feasible in the case of medium challenges to mitigation SSP scenarios, assuming that all countries work in unison. To account for the even more ambitious 1.5 °C Paris Agreement global warming targets, the RCP1.9 pathway was additionally created; however, only SSP1 scenarios managed to reliably achieve this objective (Rogelj et al., 2018).

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[4] Radiative forcing is a measure of the difference between incoming and outgoing energy in the Earth's atmosphere. Should the incoming energy be superior to the outgoing energy, then radiative forcing leads to rising surface temperatures; human-induced GHG emissions contribute to this very phenomenon (IPCC, 2023).

As of Hausfather (2018), six IAMs exist to evaluate combined SSP and RCP pathways; we will be relying on REMIND (Luderer et al., 2023) for creating our pLCI DBs. Furthermore, our chosen SSP and RCP pathways are in line with the ESM ISAaR's scenario and climate target assumptions, which will be further detailed in Section 4.1. For now, let us just say that we will be considering business-as-usual trends, i. e. SSP2, with a collective striving towards keeping global warming under 2 °C, i. e. RCP2.6. The REMIND implementation of this pathway further grants a peak budget of 1150 Gt CO_2 in the time interval 2020-2100, after which GHG emissions are required to decrease to meet the set target value (Luderer et al., 2023).

2.2 Energy System Modeling

An ESM is a computer-based projection of the future energy demand and supply, often for a specific country or region (Herbst et al., 2012). The ESM's time horizon and temporal resolution can vary very strongly depending on the model, as does the energy sector coverage. Similarly to IAMs, assumptions on demographic, economic, and technological developments as well as on future policies and energy market prices, have to be made. Thereby, a distinction between model-endogenous and model-exogenous parameters has to be made (Van Beeck et al., 1999); while model-exogenous parameters are constant and do not change during calculation, model-endogenous parameters are used within the model's equations and are internally evaluated by the ESM. For the sake of example, model-exogenous parameters might be population growth or GDP, and model-endogenous parameters can be the installed capacity and the energy mix.

Models can be categorized according to their analytical approach (Herbst et al., 2012; Van Beeck et al., 1999); we differentiate three main groups:

1. Top-down models are primarily based on macroeconomic relationships and describe the system using global factors and parameters but lack detailed descriptions of specific technologies or sectoral policies.
2. Bottom-up models, on the other hand, are based on simulation or optimization, which is why particular importance should be attached to a detailed model description of the technologies under consideration. However, overall macroeconomic transactions are not included in this approach.
3. Hybrid models combine top-down and bottom-up considerations and thus enable a more adequate description and projection of the energy system (Pfenninger et al., 2014).

Moreover, it is possible to classify models with respect to their underlying methodology: econometric, input-output, optimization, simulation, spreadsheet … (Van Beeck et al., 1999). Looking specifically at optimization-based ESMs, often used for forecasting, as in our case, an optimal set of technology choices is determined based on the minimization of a chosen parameter under certain constraints and boundary conditions. This chosen parameter might be the system costs, the system's GHG emissions, or the system's resource utilization. As an example of constraint, we can further cite the energy balance or climate mitigation targets.

Recalling our objectives, using an ESM is essential for estimating the energy system's endogenous future developments and retrieving internal parameters. Within this thesis, we will be recovering scenario results from the bottom-up ESM ISAaR (FfE, 2023), which we will present in the following. Additionally, we will be providing a short overview of the coupling of ESM and LCA in general, as this is what we aim to do within our framework.

2.2.1 General Overview of the Energy System Model ISAaR

ISAaR (standing for "Integrated Simulation Model for Unit Dispatch and Expansion with Regionalization", and short for "Integriertes Simulationsmodell zur Anlageneinsatz- und Ausbauplanung mit Regionalisierung" in German) is a FfE internal model for the representation of the energy supply sector, used for forecasting future energy system states and the developments leading to them (FfE, 2023). It is a mathematical representation of the European energy system expansion obtained through a linear optimization

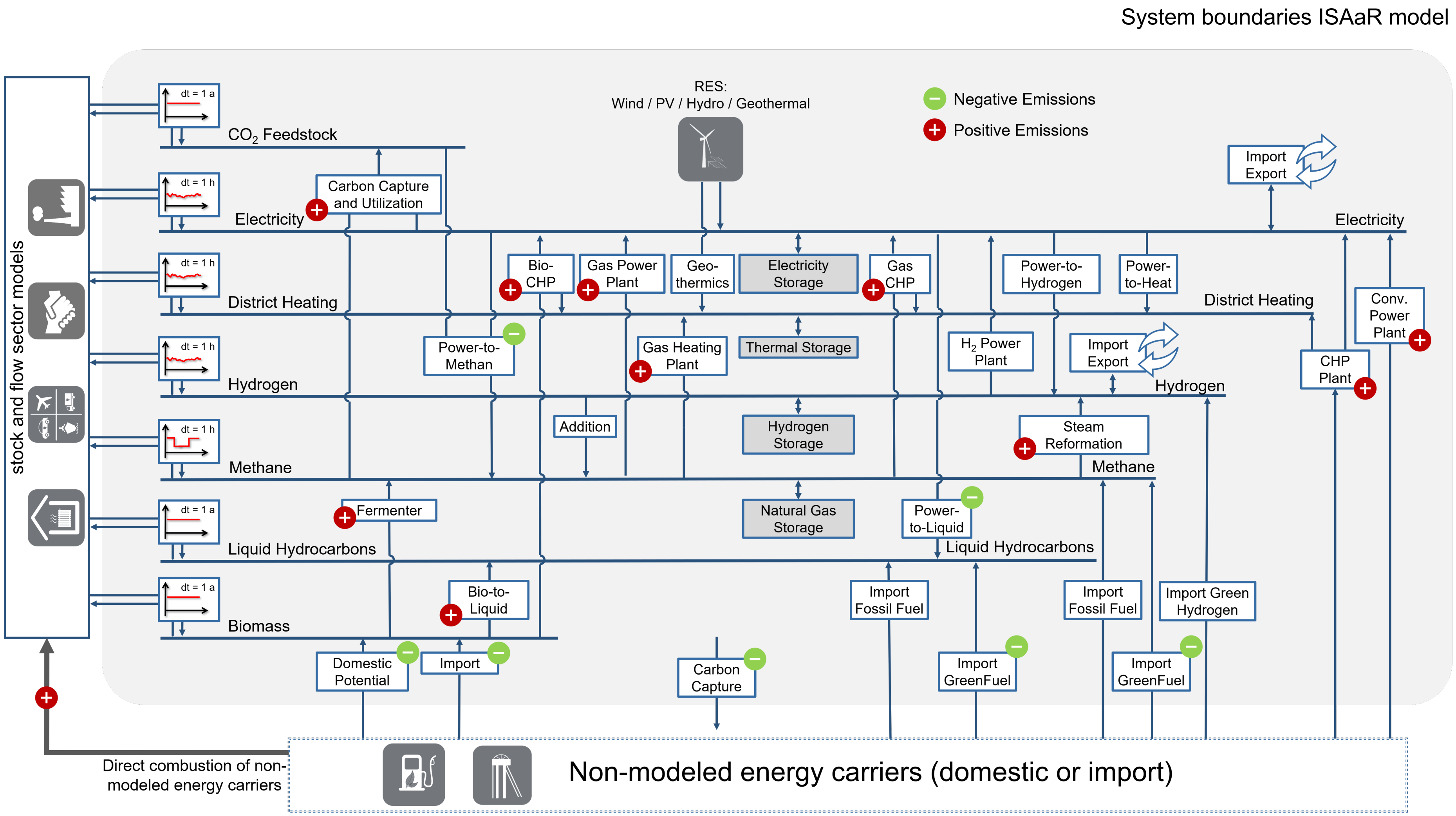

Figure 2.5 Representation of the ISAaR model structure as in FfE (2023). Particular attention is given to the coupling between energy carrier tracks and the elements within the system boundaries.

of the total system costs and building upon hourly energy sector load and RE site potential inputs. The regional resolution of the model depends on the input data and can range from individual network nodes up to several European countries; we will be focusing on Germany as a whole in this thesis. Optimization results are provided by the model in an hourly resolution and can be aggregated into bigger time steps; e. g. in this thesis, we will be contemplating five-year steps from 2025 to 2050. The DB FREM (FfE Regionalized Energy system Model) rallies all the ISAaR input and output data for a variety of evaluated scenarios; for the conception of our framework, we will be directly drawing on the model results from this DB.

Seven energy carriers, electricity, methane, hydrogen, district heating, liquid hydrocarbons, CO_2 as a feedstock and biomass, are balanced within the framework of this model on so-called energy carrier tracks, as represented in Figure 2.5. They each have assigned consumption loads, generation plants, and, if applicable, storage facilities. Energy carrier tracks are further interconnected by conversion technologies, such as Power-to-X[5], fermentation, and steam reforming. Other energy carriers, like lignite, hard coal, and oil, are also accounted for within the ISAaR framework to ensure the sufficient provision of the modeled energy carriers in addition to direct non-European imports. Those cannot be generated by conversion processes but are directly used as fuel for producing appropriate energy carriers, such as electricity or district heating, directly after their import.

At all times t, the hourly energy balance is to be guaranteed (see Böing and Regett (2019)):

$$\begin{aligned}
&\sum_{s} E_{demand}\Big(t,s,e,r\Big) = \sum_{f} E_{out}\Big(t,f,e,r\Big) - \sum_{f} E_{in}\Big(t,f,e,r\Big) \\
&\qquad\qquad + \sum_{r'} E_{import}\Big(t,e,r',r\Big) - \sum_{r'} E_{export}\Big(t,e,r',r\Big) \\
\text{with}\quad &\sum_{f} E_{out}\Big(t,f,e,r\Big) = \sum_{f_{gen}} E_{out}\Big(t,f_{gen},e,r\Big) + \sum_{f_{conv}} E_{out}\Big(t,f_{conv},e',e,r\Big) + \sum_{f_{sto}} E_{out}\Big(t,f_{sto},e,r\Big) \\
\text{and}\quad &\sum_{f} E_{in}\Big(t,f,e,r\Big) = \sum_{f_{gen}} E_{in}\Big(t,f_{gen},e,r\Big) + \sum_{f_{conv}} E_{in}\Big(t,f_{conv},e',e,r\Big) + \sum_{f_{sto}} E_{in}\Big(t,f_{sto},e,r\Big)
\end{aligned} \tag{2.2}$$

Putting this equation into words, the final energy consumption (FEC) demand for all sectors s in every considered region r has to be equal to all the power plant facilities f's energy outputs (E_{out}) minus their required energy inputs (E_{in}). Additionally, the imports and exports of energy carriers e from and to other regions r' have to be weighted in the balance. Expanding the sum of energy inputs and outputs, three types of facilities contribute to the overall balance: generation facilities f_{gen}, conversion facilities f_{conv}, and storage facilities f_{sto}. Conversion takes place to and from another energy carrier e'. In the end, Equation (2.2) mathematically translates the interconnections between energy carrier tracks as shown in Figure 2.5.

2.2.2 Coupling Energy System Model and Life Cycle Assessment

We have seen in our motivation in Section 1.1 that the energy supply sector represents one of the most polluting sectors, producing over 20% of the overall GHG emissions worldwide, which makes it an important area for action in the face of the climate challenge ahead. Still, ESMs often solely evaluate – and sometimes take into account – direct emissions occurring during the system's operational phase and caused by fuel combustion within the scope of their optimization process without considering upstream and downstream[6] emissions (Navas-Anguita et al., 2019); this is also the case in ISAaR. So it goes hand

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[5] The term Power-to-X comprises a number of electricity conversion technologies towards other energy carriers or sectors using surplus electric power, typically at times when fluctuating RES-based electricity production exceeds load. Some examples of reconversion possibilities included in this term are Power-to-Gas, Power-to-Liquid, and Power-to-Heat.

[6] We call upstream emissions, emissions that occur before a given process step, e. g. emissions linked to the provision of materials, the transport of required goods, or the construction of manufacturing facilities. On the other hand, downstream emissions concern a product's end-of-life treatment, which especially includes disposal and recycling processes.

in hand that research takes a particular interest in estimating the environmental impacts of energy system projections across their whole life cycle, or, in other words, in applying an LCA on ESM results.

Due to the high level of diverse technologies modeled by the ESM, most studies in this field make use of an LCI DB to conduct the LCA (Laurent et al., 2018). In this context, Vandepaer and Gibon (2018) highlight the challenges of matching ESM technologies with LCI DBs. Indeed, the technological and geographical resolution of the technologies rarely coincide, which raises the issue of accurately linking entities to each other. Let us define N_{ESM} as the number of technologies modeled in the ESM and N_{LCI} as the number of technologies related to the studied product category available in the LCI DB. Ideally, both resolutions are identical – $N_{ESM} = N_{LCI}$ – and the matching process does not present any significant obstacle. Should, however, the model's resolution be higher than the LCI DB's – $N_{ESM} > N_{LCI}$ – then technologies must be aggregated in the ESM to match the lack of detail in the LCI DB. On the contrary, should the LCI provide greater technological and geographical details than the ESM – $N_{ESM} < N_{LCI}$ – then model results have to be disaggregated to match the level of characterization in the LCI DB.

Taking a look at studies carrying out such a coupling between ESM and LCA, Blanco et al. (2020) outline four implementation patterns in the scope of their literature review:

1. Ex-post analysis – The LCA study is realized on specific technologies, sectors, or the overall system using static ESM post-optimization outputs. As a consequence, the model lacks feedback from the LCA results during optimization.
2. Monetization – Here, emissions are monetized as externalities and accounted for in the optimization problem. It has the advantage that environmental impacts have direct feedback on the model and the technology mix expansion. However, it is difficult to accurately monetize the impact cost.
3. Multi-objective optimization – As opposed to monetization, emissions constitute a separate objective in the optimization problem. While this helps to counteract the uncertainties linked with monetizing externalities, it raises the issue of handling a higher model complexity and creating a trade-off situation between the objectives. In literature, models have been too complex to consider other impact indicators than GHG emissions (Blanco et al., 2020).
4. Multi-criteria decision analysis – This methodology works similarly to multi-objective optimization but additionally includes qualitative aspects such as social impacts, political drivers, resource management, and risk evaluation. This allows for a holistic approach covering a wider set of dimensions, yet the importance given to each objective has to be carefully chosen.

We will be applying an ex-post analysis approach for coupling ESM and LCA within the differential viewpoint adopted in the scope of this thesis, as later discussed in Section 3.1.

Beyond the previous considerations, the evolution of technology solutions and efficiencies is inherent to the energy system and should thus be accurately mirrored by the LCA (Laurent et al., 2018). Several studies already combine ESM results with pLCA (Astudillo et al., 2019; Junne et al., 2021; Luderer et al., 2019; Volkart et al., 2018; Xu et al., 2020b); most of them employ one of the above methodologies to the evaluation of the potential effects of decarbonizing the power industry. As mentioned in our literature review in Section 1.2, only Xu et al. (2020a,b) employ an ESM for the assessment of ecological impacts related to charging strategies. To our knowledge, no framework for the automated evaluation of the impacts of a future measure or policy on the energy system, considering a differential point of view, already exists.

Chapter summary *Within this chapter, we have, as a first step, presented the LCA framework, which builds upon four implementation steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. In practice, LCAs are often conducted numerically with the help of adequate software environments and LCI DBs for modeling background processes: within this thesis, we will be using the Brightway2 Python library and the ecoinvent 3.8 cut-off version DB. As a second step, we have discussed energy system modeling as a way to make projections on future energy system states. Since the expansion of the energy system brings forth (new) technology developments, we will couple ESM and pLCA for the future-oriented assessment of the system's environmental impacts: for this, we will create scenario-based pLCI DBs with the help of the Python framework* premise. *We will further draw upon the holistic ESM ISAaR to retrieve endogenous energy system results.*

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3 Methodology for the Conception of an Automated Prospective Life Cycle Assessment Framework

We recall our main objective as being the evaluation of the future-oriented life cycle environmental impacts of the deployment of V2G strategies from an energy system's perspective. To this end, we would like to conceive an automated framework that realizes such an assessment for any given measure. While the previous chapter presented an overview of the "ingredients" – ISAaR scenario results, ecoinvent pLCI DBs – and "cooking appliances" – pLCA methodology, Brightway2 software environment – needed for this purpose, this chapter is now dedicated to the "recipe" and step-by-step instructions by which the framework in itself has been conceived.

Goal and structure of the chapter *Within this chapter, we present the methodology set up for the conception of the automated framework, thereby tackling our first research question. Special attention will be given to the theoretical implementation and general workflow of the framework, whereas V2G scenario-specific considerations and results will later be covered in Chapter 4. At no point will we go into programming details but remain on a theoretical level. Regarding the chapter's organization, we will first sketch the framework's outline and, afterward, proceed in chronological implementation order, which heavily leans on the four LCA steps.*

3.1 General Workflow of the Automated Framework

A distinctive trait of the framework is the coordination of a variety of miscellaneous software environments, each serving a unique purpose and rendering different results wrought together to achieve the specified objective. Thus, this section serves to introduce the workflow of the framework, specifying the obtained intermediary results in each step in a general way. Implementation details will be tackled in the remainder of this chapter.

First, let us recall that we will be conducting a pLCA from a differential perspective, i. e. on the difference in energy system expansion results between a scenario implementing a given measure and one which does not. As discussed in Section 2.2.2, our concept relies on the coupling between ESM and pLCA. We proceed with an ex-post analysis, meaning that we take static ESM results and that the evaluated environmental impacts are at no point fed back to the ESM. As a consequence, we do not need to interact with the ESM in itself; its exact working principle lies beyond the scope of this thesis. The lack of feedback has been highlighted by Blanco et al. (2020) as being the main disadvantage of the chosen coupling methodology, as the energy system expansion would ideally be influenced by the assessment results. However, as recalled, we apply a differential point of view only for our assessment, and consequently, at no time do we obtain absolute results to communicate to the ESM. That is why we deem the decision of using an ex-post analysis relevant in our case. In practice, we individually retrieve static ISAaR endogenous parameter results directly from the DB FREM for both analyzed scenarios. Those results have been evaluated beforehand and do not belong to the contributions of this thesis. Let us call "reference scenario", the scenario where no additional measure is deployed, and "altered scenario", the scenario accounting for the changes induced by a certain measure; we are then interested in the difference between the altered scenario with respect to the reference scenario.

We further discussed in Section 2.2.2 that, according to Vandepaer and Gibon (2018), the main challenge in such a coupling between ESM and LCA resides in matching the ESM technologies with technologies from an LCI database to model the background processes. Relating this issue to the assessment of

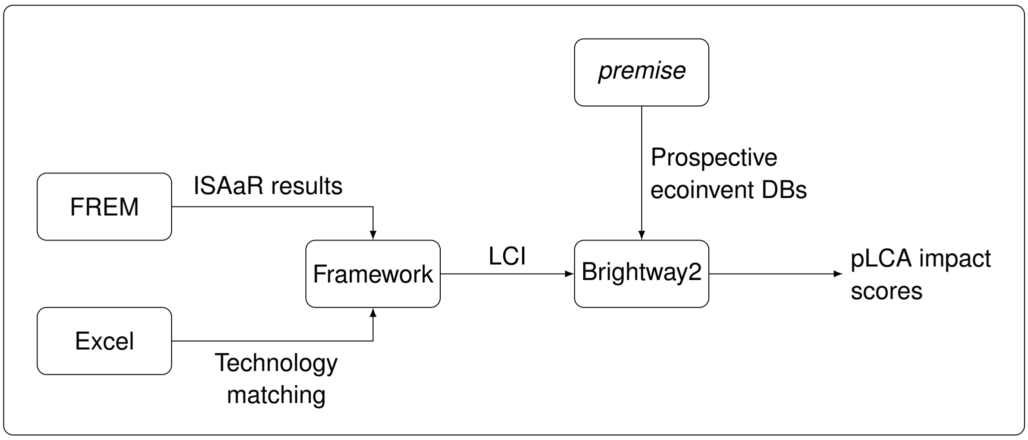

Figure 3.1 Simplified outline of the automated framework's workflow

the energy system, a "technology" could, for example, be the construction of a certain capacity of PV panels or the generation of a certain amount of energy stemming from the combustion of natural gas. We use Microsoft Excel to perform such a matching and adjust technologies to the same aggregation level. Let us, however, note that due to the relatively low ISAaR technology resolution, no aggregation of parameter results is needed in our case, only disaggregation. On the basis of this matching and the difference in ISAaR results between the reference and altered scenario, it is possible to establish an LCI of the technologies and amounts featured in the difference. The prospectively adapted ecoinvent LCI DBs then provide the background processes to our LCI and can be used by the Brightway2 framework to compute a variety of pLCA impact scores. The diagram in Figure 3.1 illustrates the simplified framework workflow, which we have just described.

Let us now elaborate on the general step-by-step implementation of the framework. Complementarily to the previous figure, the sequence diagram in Figure 3.2 visualizes the overall chronological program dynamics and the interactions between the various entities composing our framework. We distinguish five entities:

1. The framework in itself – by which we understand the Python program files and functions, allowing for the interactions between all other entities and processing intermediary results.
2. The user – i. e. the person using the framework to evaluate the impacts of a measure of interest.
3. The Brightway2 library – which carries out all operation steps linked to the LCA in itself. We use it to manage ecoinvent (p)LCI databases and impact indicators, perform the LCIA calculation, and help in analyzing the results.
4. The FREM DB – which gathers all ISAaR parameter results for different scenarios. Thereby, the measure to be assessed needs to have been evaluated by the model beforehand, thus already featuring scenario results in FREM.
5. The Excel matching file – which takes the form of a list of correspondences between ISAaR parameter technologies and ecoinvent processes, additionally containing information on required adjustments between both.

We assume that the ecoinvent pLCI DBs have already been generated by the user in a local Brightway2 project prior to executing the framework. When launching our framework, the user is first and foremost prompted to enter settings on the desired evaluated measure and impacts. Hereafter, the framework performs a few initialization steps, in particular, establishing a connection to the FREM DB, retrieving the project in Brightway2, and obtaining a list of the ecoinvent pLCI DBs fitting the ISAaR scenarios' energy system expansion years. Thereupon, the actual assessment steps are executed. We differentiate three energy system life phases which can be evaluated individually or in combination within one framework run: the construction, the fuel consumption, and the end-of-life treatment of power plant facilities, which can be paralleled to the gate, use, and grave phases of a product's life cycle as in Figure 2.2. The life phases are assessed separately by the framework within a loop structure; whence, the next steps are reiterated

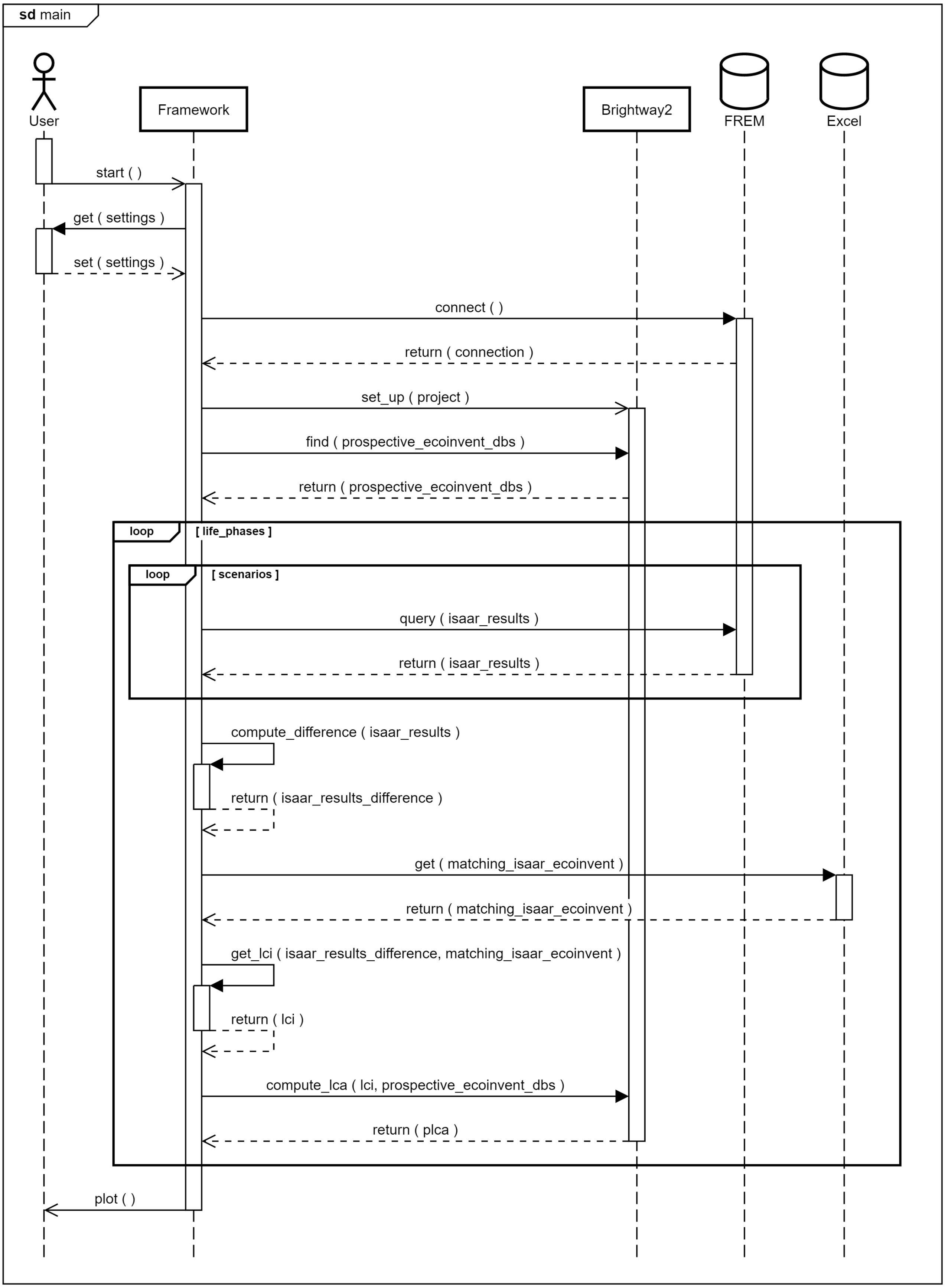

Figure 3.2 Sequence diagram for the automated framework's overall proceedings and interactions

for each phase. To begin with, the ISAaR endogenous parameter results corresponding to the appraised life phase are retrieved from FREM for each of the two scenarios. Once this is done, it is possible for the framework to compute the difference between both scenario results. Fetching the ecoinvent process matching for the technologies featured in the difference and combining this with the value to which the difference amounts, the framework is then able to generate an LCI for each evaluated energy system expansion year. The Brightway2 environment can then directly use this LCI to compute the indicator scores of multiple impact categories based on the appropriate ecoinvent pLCI DB background process information. Lastly, the framework plots results.

3.2 Implementation of the Prospective Life Cycle Assessment Methodology within the Framework

Let us now go into more detail on the underlying operating principle of the framework, in particular elucidating what lies behind the functions related to the pLCA in the sequence diagram. The framework concept has been developed around the four steps of the LCA methodology, as presented in Section 2.1.1. Hence, in the following, we will go over how each step was carried out to cover our specific use case and how it can be implemented to meet the automation requirement of the framework.

3.2.1 Goal and Scope Definition

Goal First, let us state the goal of our framework. As mentioned several times, it serves to evaluate the environmental impacts that deploying one policy, measure, or technology might have on the energy system as a whole in the future. The evaluation takes on a differential perspective, thus looking at the energy system expansion divergence from a scenario implementing the measure to be appraised to one that does not. In our concrete case, the framework has been created for application on V2G strategies as covered by Chapter 4. As no absolute results are output by the framework, we can only make comparison-based findings between both scenarios and cannot draw general conclusions. Moreover, any non-environmental advantages or drawbacks of implementing the measure or not are not taken into account within the assessment but play a crucial role in decision-making nonetheless.

System As to the scope of the framework, we define the system under consideration as being the difference in the energy system expansion required to cover the energy demand in both scenarios – this is the function of the system. We separate the additionally needed expansion of one scenario with respect to the other scenario, thus conducting the pLCA on these supplementary needs for each scenario separately. This has the advantage of accurately associating positive and negative (e. g. stemming from carbon capture technologies) environmental impacts to the scenario involved. Results are then given with respect to the entirety of the additional endogenous system expansion required by one scenario with respect to the other; in other words, the functional unit of the system is the ancillary power plant park expansion needed in one evaluated year for the sufficient energy generation and storage in the future energy system. The temporal scope of the assessment takes place in the future, with the exact assessed expansion years being linked to the ISAaR scenario model runs; most scenarios are evaluated in five-year steps starting from 2025 and going up to 2050. As to the regional scope of the assessment, the framework has been thought to work for any country within the modeled ISAaR regions or for Europe as a whole; however, the practical application has been focused on Germany so far.

System boundaries In the case of our differential point of view, it is particularly relevant to precisely define the system boundaries. In general, it can be said that our assessment comprises all required investments in the energy supply sector in a given year to successfully cover the energy demand; thereby, we consider the whole life cycle of those investments meaning that we cover all their upstream and downstream processes. We do not cover any investments linked to the energy distribution or FEC sectors within this framework but stick with the energy supply sector. Figure 3.3 depicts the framework's system boundary as just described. Concretely, we include two major energy supply system investments in our pLCA: the construction of new generation and storage facilities and the production of sufficient energy to satisfy the demand. The latter can be reformulated as the provision of energy carriers obtained through conversion processes from other energy carriers, which are either imported into the system or internally generated. With this boundary, we cover two major life phases associated with power plants: their manufacturing and their use phase. To complete the life cycle of energy supply facilities and thus conduct a comprehensive assessment, we would also need to account for their dismantling upon reaching their end-of-life as well as for the waste generation and treatment due to energy production. Yet, at this stage, we have not been able to properly ponder the disposal and recycling of power plant facilities and waste within the framework due to a lack of documentation on this topic in the ecoinvent database; indeed, some facility construction and fuel combustion processes already take this information into account whereas others do not. As it would have been too troublesome within the scope of this thesis to accurately address this life phase given the time circumstances, we left it out of our considerations and are conscious of the disparities this brings forth. As it is, this constitutes a major limitation to our framework to date.

ISAaR endogenous model parameters can be used to assess each life phase. Regarding the construction of facilities, we seek to quantify the capacity taken into operation between two expansion years and attribute the entirety of the construction impacts to this time step, whence the impacts of facilities constructed in the past are not assessed within our framework. Moreover, we evenly distribute the construction impacts of a time step among the expansion years comprised in that time step. The amount of newly built energy generation or storage capacity can be calculated based on the difference in installed capacity between two consecutive expansion years. To correctly account for the constructed capacity, we also compensate for the extent of capacity dismantled as they reach their end-of-life.

As to the use phase, ISAaR yields results on the provision of energy carriers either as direct imports to the energy carrier tracks or as fuel for the conversion to other energy carrier tracks (see Figure 2.5). This information is given by ISAaR for one evaluated expansion year; we hypothesize that all years comprised within a time step have the same requirements in energy carriers as the evaluated expansion year. To avoid double counting of impacts within the energy system (Lenzen, 2008), some assumptions and ISAaR-specific considerations have to be made. For simplification and relevance reasons, we confine our-

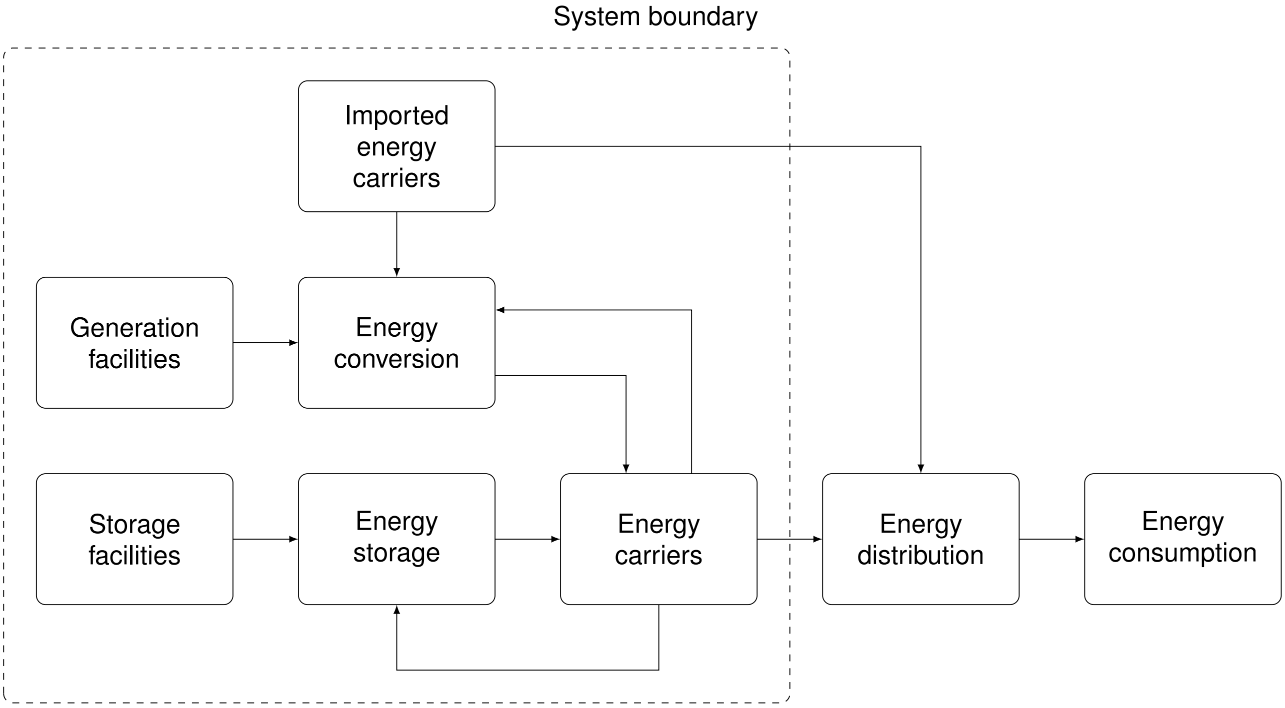

Figure 3.3 Diagram of the energy supply sector as being our framework's system boundary

selves to CO_2 emissions in the following discussion. First, a distinction must be made between imported energy carriers and internally produced energy carriers. Concerning internally produced energy carriers, the CO_2 emissions attributed to the conversion process are compensated by the system in itself: either because their combustion process has near zero emissions or because it is offset, e. g. due to negative generation emissions (as in the case of green fuels) or carbon capture techniques (as in the case of synthetic fuels). As the consumption of such fuels with offset emissions only takes place within the country where it was produced in ISAaR, no impact attributions between countries have to be made, and they can be neglected within our boundary. In short, we do not need to track conversion processes involving internally produced energy carriers within our assessment. Furthermore, we specify that our system boundary only includes investments required by the energy supply sector for providing energy to other sectors; thus, we do not account for the direct import of energy carriers towards the FEC sectors. This implies that, within the import category, we merely assess the import of energy carriers for conversion purposes. In the case of fossil energy carrier imports, we straightforwardly account for their provision and combustion as part of the overall conversion procedure. Now taking a look at green and synthetic energy carriers, we have just seen that their combustion is offset within their production process. This leaves two methods available to us for their consideration within our framework; the first one is to attribute negative emissions to their production and positive emissions to their combustion, while the second one consists of solely taking into account upstream and downstream emissions for the provision of the energy carrier, neglecting the combustion and its compensation within the generation process as they cancel out. For data availability reasons within ecoinvent, we choose the second approach.

This leaves two ISAaR technologies that have not yet been covered in our boundary definition: carbon capture and utilization (CCU) and carbon capture and storage (CCS). CCU is a procedure that intercepts carbon emissions arising from industrial processes and consumes them in other processes, mainly within the energy supply sector and especially for the production of synthetic fuels. Likewise to imported synthetic energy carriers, we then have negative emissions when introducing the carbon into the system boundary and positive emissions when burning the fuel. As these cancel out, this leaves us with assessing the impacts of the facilities required for the conversion process. However, we already include them within the construction phase, whence we do not need to track CCU application within our pLCA. Last but not least, we are left with discussing CCS. For this, it is important to know that, in ISAaR, all emissions originating from direct fuel combustion are modeled as an endogenous parameter, even if they are not taken into account within the optimization process. All excess emissions with respect to the official national and international climate policies in place are then aggregated to the CCS process; in other words, in ISAaR, CCS represents all energy system emissions that need to be secluded from the atmosphere in order to reach the set climate targets. At this stage, we hypothesize that the entirety of these emissions will be captured using CCS as a technology as opposed to storing it in natural sinks. As CCS renders negative CO_2 emissions, we need to take this process into account within our system boundaries. Due to the ISAaR result portrayal, we wholly consider CCS as a use phase technology, even including the construction of adequate facilities within this phase.

Within our differential viewpoint, we only assess the additional investments included in the just defined energy supply sector boundaries of each scenario with respect to the other one, thus leaving aside all investments that are mutual to both scenarios. Should one scenario need to make investments that can be attributed to two sectors – comprising the energy supply sector – then we only consider the additional investment made with respect to the other scenario in order to guarantee the energy supply.

Allocation Allocation procedures become relevant in energy system assessments when facilities or energy carriers can be employed to yield more than one energy carrier type; a prominent example of this are combined power and heat generation plants. Impact contributions then need to be allocated between the different energy carriers. However, a particularity of our system boundary is that we do not single out specific energy carriers but include all energy types within our assessment. As a consequence, all allocation parts related to the individual generation of distinct energy carriers are included within the boundary: it is thus unnecessary to conduct such an allocation procedure within our framework.

User settings All supplementary information relevant to the goal and scope definition is settled by the framework user himself: this chiefly comprises the justified choice of impact categories and the scope of result interpretation. As already mentioned in Section 3.1, the user is presented with a set of options to specify prior to the framework operation. These options can be divided into three main categories: 1) settings related to the scenario selection in ISAaR, 2) settings related to pLCA scope, and 3) settings related to result plotting and analysis. It shall, however, be noted that some of them are purely functional and do not contribute to the goal and scope definition and, in more general terms, the pLCA; these parameters solely benefit the automation and operation of the framework. Table 3.1 summarizes the framework automation settings that can be defined by the user according to the previous classification. Settings may be saved by the framework between two runs for a more flexible user experience.

ISAaR settings		**pLCA settings**		**Plot settings**	
Name	*Functional?*	*Name*	*Functional?*	*Name*	*Functional?*
Reference scenario key	–	Brightway2 project name	✓	Plotting results	✓
Altered scenario key	–	Ecoinvent version	✓	Saving plots	✓
Region type key	–	IAM scenario	–	Expansion years to plot	–
Region key	–	Assessment of the construction phase	–		
		Assessment of the use phase	–		
		Assessment of end-of-life	–		
		Impact categories	–		

Table 3.1 Table of user settings prompted by the framework. Parameters are differentiated between functional parameters (✓) and parameters serving the use-case-specific goal and scope definition (–).

ISAaR settings are all related to locating the results associated with the desired scenarios and regional scope in the FREM DB; this is done via SQL primary keys within the *query(isaar_results)* function portrayed in the sequence diagram in Figure 3.2. Next, the first three pLCA settings – the Brightway2 project name, the ecoinvent version, and the IAM scenario name – serve to accurately and single-handedly identify the correct ecoinvent pLCI DBs within the Brightway2 project as part of the sequence diagram's *find(prospective_ecoinvent_dbs)* step. With the three "assessment [...]" options, the user may choose which of the power plant facilities' life phases to assess. He must further select an unrestricted number of impact categories from a list and, by doing so, pick which environmental aspects to investigate. Lastly, the user may choose to plot results in his use-case relevant expansion years, thus influencing the temporal scope of the analysis; generated plots can be automatically saved.

3.2.2 Inventory Analysis

The automated establishment of the LCI is realized within two framework steps: 1) querying the scenario-specific ISAaR results from FREM and quantifying the additional life phase investments of each scenario with respect to the other one, and 2) matching and adjusting the technologies featured in the difference with adequate ecoinvent processes. In the following, we will describe the mathematical calculation steps and automation procedures this requires.

3.2.2.1 Computing Disparities Between Scenarios

This step can be likened to a practical implementation of our previous system boundary definition, as life phase disparities between both scenarios are quantified for further assessment. Relating this step with the sequence diagram in Figure 3.2, it is executed within the generic *query (isaar_results)* and *compute_difference (isaar_results)* functions and takes on a different form according to the life phase under consideration; hence, we will treat each life stage separately in the upcoming discussion.

Construction phase As stated in our system boundaries, the actual amount of facility capacity taken into operation in a given expansion year can be calculated based on the installed capacity output in all evaluated expansion years. In ISAaR, installed capacity amounts are aggregated according to their technology type: some illustrative examples of this are ”offsite PV”, “gas turbine”, and “hydrogen storage”. Generation capacities are expressed in MW of installed power and storage capacities in MWh of installed storage provision. The following discussion holds for generation and storage facilities alike.

Let us define a set $\mathcal{E}$ representing the expansion years as follows:

$$\mathcal{E} = \left\{ t_k \in \mathbb{N}_+ \,\middle|\, t_k = t_0 + k \cdot N_s \, , k \in \mathbb{Z} \right\} \tag{3.1}$$

t_0 stands for the first evaluated expansion year while $N_s \in \mathbb{N}_+$ characterizes the time step between two evaluated years; for the sake of example, in a majority of ISAaR scenarios, $t_0 = 2025$ and $N_s = 5$. With regard to our use-case, we assume that every year in $\mathcal{E}$ prior to t_0 lies in the past.

In accordance with the established notation in Section 2.2.1, f denotes one individual facility type be it for energy generation or storage, and e and r respectively stand for the energy carrier and region under consideration. For any ISAaR technology f, the installed capacity of a scenario *sce* for an expansion year $t_k \in \mathcal{E}$ shall be denoted as $P^{(sce)}_{inst}\left(t_k, f, e, r\right)$; this value is given by the FREM DB and forms the basis of our constructed capacity calculations. As a next step, the facility type’s increase or decrease in capacity available to the system for a year t_k with respect to the previous expansion year t_{k-1} can be expressed recursively as the difference between the currently installed capacity and the previous expansion year’s installed capacity. This is what we call the net constructed capacity:

$$P^{(sce)}_{net}\left(t_k, f, e, r\right) = P^{(sce)}_{inst}\left(t_k, f, e, r\right) - P^{(sce)}_{inst}\left(t_{k-1}, f, e, r\right) \tag{3.2}$$

We introduce $N_l \in \mathbb{N}_+$ as being the lifetime of the considered power plant. Then the expansion year this power plant was built in lies $n = \left\lceil \frac{N_l}{N_s} \right\rceil$ time steps in the past. Hence, for an expansion year $t_k \in \mathcal{E}$, the amount of capacity to be dismantled after reaching the end of the lifetime of the power plant can be written in terms of a past net constructed capacity:

$$P^{(sce)}_{dis}\left(t_k, f, e, r\right) = P^{(sce)}_{net}\left(t_{k-n}, f, e, r\right) \tag{3.3}$$

Finally, the gross constructed capacity represents the capacity equivalent of investments in power plants in a given expansion year while compensating for the necessary power plant dismantling in that same year. Hence, when making the sum of the net constructed capacity and the dismantled capacity for an expansion year t_k, we account for the actual capacity amount constructed and taken into operation in that year, thus complying with the defined system boundary:

$$P^{(sce)}_{gross}\left(t_k, f, e, r\right) = P^{(sce)}_{net}\left(t_k, f, e, r\right) + P^{(sce)}_{dis}\left(t_k, f, e, r\right) = P^{(sce)}_{net}\left(t_k, f, e, r\right) + P^{(sce)}_{net}\left(t_{k-n}, f, e, r\right) \tag{3.4}$$

Now, let us consider two scenarios in order to be in line with our framework concept; we denominate them as *ref* for reference scenario and *alt* for altered scenario. Hence, their installed capacity is denoted as $P^{(ref)}_{inst}$ and $P^{(alt)}_{inst}$, respectively. In the scope of our assessment, we are actually interested in the difference in gross constructed capacity for each power plant type, which based on the previous reasoning, can be expressed as follows:

$$\begin{aligned} &P_{gross}^{(alt)}\left(t_k, f, e, r\right) - P_{gross}^{(ref)}\left(t_k, f, e, r\right) \\ &\quad = \left[P_{net}^{(alt)}\left(t_k, f, e, r\right) + P_{net}^{(alt)}\left(t_{k-n}, f, e, r\right)\right] - \left[P_{net}^{(ref)}\left(t_k, f, e, r\right) + P_{net}^{(ref)}\left(t_{k-n}, f, e, r\right)\right] \end{aligned} \tag{3.5}$$

Taking Equation (3.2), we can rewrite the equation above in function of the installed capacity, and thus of an endogenous model parameter directly given by ISAaR:

$$\begin{aligned} &P_{gross}^{(alt)}\left(t_k, f, e, r\right) - P_{gross}^{(ref)}\left(t_k, f, e, r\right) \\ &\quad = \left[\left(P_{inst}^{(alt)}\left(t_k, f, e, r\right) - P_{inst}^{(alt)}\left(t_{k-1}, f, e, r\right)\right) + \left(P_{inst}^{(alt)}\left(t_{k-n}, f, e, r\right) - P_{inst}^{(alt)}\left(t_{k-(n+1)}, f, e, r\right)\right)\right] \\ &\quad\quad - \left[\left(P_{inst}^{(ref)}\left(t_k, f, e, r\right) - P_{inst}^{(ref)}\left(t_{k-1}, f, e, r\right)\right) + \left(P_{inst}^{(ref)}\left(t_{k-n}, f, e, r\right) - P_{inst}^{(ref)}\left(t_{k-(n+1)}, f, e, r\right)\right)\right] \end{aligned} \tag{3.6}$$

If *diff* now describes the difference in capacity of the altered scenario with respect to the reference scenario within a year $t_k \in \mathcal{E}$, we can rewrite Equation (3.6) more compactly:

$$\begin{aligned} &P_{gross}^{(diff)}\left(t_k, f, e, r\right) \\ &\quad = P_{inst}^{(diff)}\left(t_k, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-1}, f, e, r\right) + P_{inst}^{(diff)}\left(t_{k-n}, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-(n+1)}, f, e, r\right) \end{aligned} \tag{3.7}$$

Now, should an expansion year lie in the past, which, according to our previous assumption, is true for any year t_k with $k < 0$, then the amount of installed capacity for that year is given by fixed historical values and cannot differ between scenarios. Thus, in that case, the difference in installed capacity between the two scenarios is null. From this, we can distinguish four cases for the computation of the difference in gross constructed capacity for future expansion years $t_k \in \mathcal{E}$, $k \geq 0$[1]:

$$P_{gross}^{(diff)}\left(t_k, f, e, r\right) = \begin{cases} P_{inst}^{(diff)}\left(t_k, f, e, r\right) & \text{for } k = 0 \\ P_{inst}^{(diff)}\left(t_k, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-1}, f, e, r\right) & \\ \quad + P_{inst}^{(diff)}\left(t_{k-n}, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-(n+1)}, f, e, r\right) & \text{for } (k-n) > 0 \\ P_{inst}^{(diff)}\left(t_k, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-1}, f, e, r\right) + P_{inst}^{(diff)}\left(t_{k-n}, f, e, r\right) & \text{for } (k-n) = 0 \\ P_{inst}^{(diff)}\left(t_k, f, e, r\right) - P_{inst}^{(diff)}\left(t_{k-1}, f, e, r\right) & \text{for } (k-n) < 0 \end{cases} \tag{3.8}$$

Remarkably, it becomes apparent that historical data is not needed at all within the differential point of view opted for within the scope of the pLCA. Moreover, it can be seen that it is possible to compute the difference in gross constructed capacity solely from the difference in installed capacity, which can be easily determined via ISAaR results for each scenario. Power plant types for which the difference in installed capacity is null for all future expansion years do not need to be considered within the scope of the assessment.

In truth, the formula we have just worked out in Equation (3.8) represents the gross constructed capacity difference in a time step and not for a unique evaluated expansion year. We recall that we evenly distribute the construction impacts of a time step among the years comprised within that time step; thus, in order to obtain the actual construction difference in one expansion year t_k, we need to divide the result by the number of years comprised a time step, i. e. by N_s. Furthermore, we do not conduct our assessment with the difference between the two scenarios but with the additional scenario investments with respect to the other scenario to accurately attribute potential negative impacts. Hence, taking the difference in

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[1] For past expansion years $t_k \in \mathcal{E}$ with $k < 0$, this difference will always be equal to zero.

construction between both scenarios as previously defined, we assign positive values as being additional investments in the altered scenario and negative values as being additional investments in the reference scenario.

Use phase We have seen in our system boundary discussion that, within the scope of our pLCA, for evaluating the use phase of the energy system, it is sufficient to account for the energy supply sector's acquisition – and, in the case of fossil resources, combustion – of primary energy carriers. Hence, for inventory calculations, we need to retrieve the amount of imported energy used for conversion purposes from ISAaR. The inclusion – or not – of an energy carrier's combustion in the LCI is later regulated through an accurate process matching in ecoinvent, which is why the following procedure holds for all energy carriers – green, synthetic, and fossil – portrayed in ISAaR. Nevertheless, ISAaR solely provides results for the overall energy carrier imports, be they used for conversion processes or for directly satisfying the FEC (see Figure 3.3). As a consequence, we have to compute the import part attributed to the energy supply sector only; we do this by subtracting the share of imports allocated to the FEC. From ISAaR, we can retrieve two pieces of information for computing this value: 1) the total import of different energy carriers and 2) the total and FEC-specific demand in each energy carrier.

First, let us explain our procedure with an example. For this, we need to distinguish two terminologies for characterizing energy carriers: the first one is the energy carrier type in itself (e. g. gas), and the second one is the provision alternative of that energy carrier type (e. g. green methane or natural gas). Now, let us suppose that we stick with the energy carrier type gas: a mock energy balance in a fictive expansion year for this energy carrier type is represented in Figure 3.4. The supply of gas needed to cover the total demand is assured by the energy system's own gas production and by gas imports. Within the gas imports, we differentiate two gas provision alternatives: natural gas and green methane. We recall that for each energy carrier provision alternative, we want to deduce the part of imports allocated to the FEC sectors from the total imports in order to obtain the part of imports assigned to the energy supply sector.

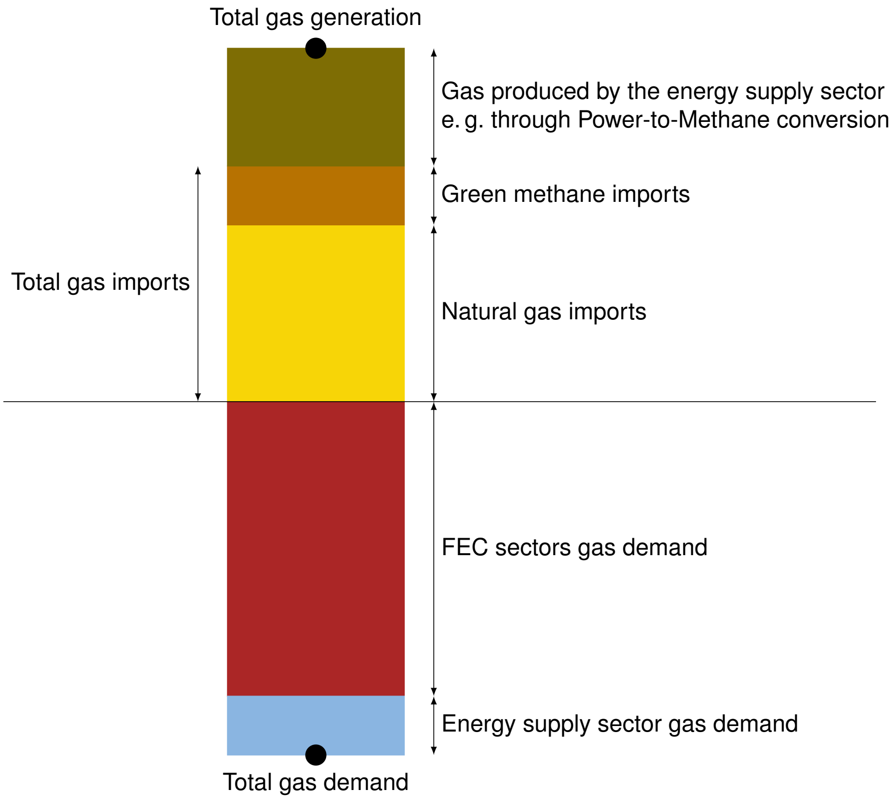

Figure 3.4 Example of an annual energy balance for gas as an illustrative energy carrier type. Values have been chosen arbitrarily and do not correspond to reality.

Hence, in the case of our example, we want to know which part of the natural gas/ green methane imports goes into meeting the FEC demand for gas. In the following, we hypothesize that imports are distributed towards the FEC sectors and the energy supply sector proportionally to their demand. In simpler words, this means that if the FEC sectors' demand for gas represents, for example, 80% of the total gas demand, then we allocate 80% of each's gas provision alternative imports to the FEC sectors. Consequently, 20% of the natural gas/ green methane imports actually go into the energy system. It shall be noted that this assumption was made due to a lack of ISAaR information in this regard and does not necessarily reflect reality.

Now, let us formulate this proceeding mathematically for any energy carrier type. First, in alignment with the notations introduced in Section 2.2.1, let us denote the demand in the energy carrier type e in an expansion year $t_k \in \mathcal{E}$ as:

1. $\sum_s E_{demand}\left(t_k, s, e, r\right)$ – for the FEC sectors;
2. $\sum_f E_{demand}\left(t_k, f, e, r\right)$ – for the energy supply sector.

While the FEC sector's demand can be retrieved from FREM, we do not have direct access to the energy supply sector's demand. However, by querying the value for the total energy carrier type demand $\sum_s E_{demand}\left(t_k, s, e, r\right) + \sum_f E_{demand}\left(t_k, f, e, r\right)$, we can compute the share of FEC demand with respect to the total demand:

$$share^{(FEC)}_{demand}\left(t_k, e, r\right) = \frac{\sum_s E_{demand}\left(t_k, s, e, r\right)}{\sum_s E_{demand}\left(t_k, s, e, r\right) + \sum_f E_{demand}\left(t_k, f, e, r\right)} \tag{3.9}$$

In accordance with our previous hypothesis, for each energy carrier provision alternative e_{alt}, the share of imports allocated to the FEC sectors $share^{(FEC)}_{import}$ is equal to the share of FEC-specific demand with respect to the total demand. Hence, we can write:

$$share^{(FEC)}_{import}\left(t_k, e_{alt}, r', r\right) = share^{(FEC)}_{demand}\left(t_k, e, r\right) \tag{3.10}$$

Consequently, the share of imports allocated to the energy supply sector (*ESS*) is equal to:

$$share^{(ESS)}_{import}\left(t_k, e_{alt}, r', r\right) = \left[1 - share^{(FEC)}_{import}\left(t_k, e_{alt}, r', r\right)\right] = \left[1 - share^{(FEC)}_{demand}\left(t_k, e, r', r\right)\right] \tag{3.11}$$

Let us designate the import amount of an energy carrier type's provision alternative to a region r in an expansion year $t_k \in \mathcal{E}$ as $\sum_{r'} E_{import}\left(t_k, e_{alt}, r', r\right)$. Then, we can compute the part of imports of that alternative allocated to the energy supply sector as:

$$share^{(ESS)}_{import}\left(t_k, e_{alt}, r', r\right) \sum_{r'} E_{import}\left(t_k, e_{alt}, r', r\right) = \left[1 - share^{(FEC)}_{demand}\left(t_k, e, r\right)\right] \sum_{r'} E_{import}\left(t_k, e_{alt}, r', r\right) \tag{3.12}$$

For energy carriers that are not featured in the ISAaR energy carrier tracks but are still imported for conversion purposes – such as e.g. lignite or hard coal – these calculations stay valid. Indeed, in this case, we just have $share^{(FEC)}_{demand}\left(t_k, e, r\right) = 0$, implicating that all imports are allocated to the energy supply sector. As for CCS, we can consider its usage as being an import and thus apply the same formalism.

Returning to our differential point of view, the use phase disparities arising between the two scenarios can then straightforwardly be calculated as the difference between each energy carrier provision alternative's imports toward the energy supply sector. Again, we attribute the positive results of this difference to the altered scenario and the negative results to the reference scenario.

3.2.2.2 Matching and Quantifying Technologies

To model the background processes of the technologies – i. e. power plants and primary energy carriers – contained within the system boundary, we resort to the ecoinvent LCI database. ISAaR technologies are manually matched with ecoinvent processes through an Excel spreadsheet prior to the framework execution. Even though the spreadsheet template slightly differs according to the life phase under consideration, the overall implementation for the configuration of one technology's LCI stays identical and is realized within the "*get(matching_isaar_ecoinvent)*" and "*get_lci(isaar_results_difference, matching_isaar_ecoinvent)*" steps of the sequence diagram in Figure 3.2. We present this general working principle below and, subsequently, tackle the particularities associated with each life phase.

We set l as being a line of the matching table; each line contains one correspondence between ISAaR technology and ecoinvent process. The first four columns[2] of any line l are of interest to us in the upcoming discussion and contain the following information:

1. l_1 – the unique FREM SQL primary key characterizing the ISAaR technology;
2. l_2 – the ISAaR technologies' name as recorded in FREM;
3. l_3 – the ecoinvent process name associated with the ISAaR technology.
4. l_4 – the unit in which the ecoinvent process in l_3 is expressed.

Algorithm 1: Matching one ISAaR technology with ecoinvent processes

```
Data: $N_{key}$
Result: $LCI_{key}$;
for all lines l in matching table do
    if $l_1 == N_{key}$ then
        if $l_3 ==$ "missing" then
            warning;
        else if $l_3 ==$ "import" then
            create $l_2$ ISAaR technology in DB;
            compute $d_p$;
            $LCI_{key} \leftarrow \{process, d_p\}$;
        else
            find $l_3$ ecoinvent process in DB;
            compute $d_p$;
            $LCI_{key} \leftarrow \{process, d_p\}$;
        end
    end
end
return $LCI_{key}$
```

For any ISAaR technology featured in the assessed scenario difference and characterized by the primary key N_{key}, the ecoinvent-based LCI LCI_{key} for this technology is determined based on Algorithm 1. In other words, LCI_{key} is an inventory of ecoinvent processes and quantities corresponding to one ISAaR technology. In practice, it has been implemented within our framework as a list of tuples $\{process, d_p\}$, each containing one ecoinvent process and its associated demand d_p. First and foremost, the algorithm searches for all lines in the matching table corresponding to the technology key, i. e. where $l_1 = N_{key}$. For each line corresponding to N_{key}, the framework creates the fitting tuple and appends it to LCI_{key}. It is possible that more than one line corresponds to a unique ISAaR technology to account for different technical realizations of that technology; in that case, we are faced with what we introduced as a disaggregation situation in Section 2.2.2 and LCI_{key} is composed of multiple ecoinvent process tuples. This implies that we have to know the proportion of the ISAaR technology produced with one alternative for computing the

---

[2] For any line l, we denote the entry in column j and line l as l_j.

demand d_p. Furthermore, it is important to note that d_p is computed differently according to the facility life phase under consideration (see upcoming discussion relative to each life phase).

Three different scenarios can arise in Algorithm 1 when having a line in the matching table corresponding to the ISAaR technology key we are looking for, i. e. when $l_1 = N_{key}$. Let us take a closer look at the information contained within the third column entry of such a line:

1. The ecoinvent process name in l_3 is indicated as "missing" – then a warning is given to the user, and the process is further ignored by the framework; thus, it is not accounted for within LCI_{key} and, by extension, the pLCA as a whole.
2. The ecoinvent process name in l_3 is indicated as "import" – then no direct ecoinvent process corresponding to the ISAaR technology exists within the DB. Nevertheless, in contrast with the previous case, LCI information on this technology, stemming e. g. from literature, has been manually recorded within a separate Excel spreadsheet prior to the framework execution. A new ecoinvent process for this technology l_2 is then created by the framework based on that dedicated spreadsheet. We highlight that the Excel spreadsheet needs to comply with a predefined template for full framework automation.
3. The ecoinvent process name in l_3 is neither of the above – then the framework estimates that an ecoinvent process name has indeed been stored in this line entry and thus searches for the process l_3 having the unit l_4 in the ecoinvent DB. The framework then automatically chooses the DB entry matching the lowest region aggregation corresponding to the region under consideration. In simpler words, should the scope of our assessment, for example, be Germany, then the framework first looks at if an ecoinvent entry, complying with the l_3 and l_4 conditions, exists for Germany; if this is not the case, then it searches for an entry assimilated with Europe, and so forth, until reaching an entry with a worldwide aggregation level. In the event that no fitting entry can be found, the algorithm applies the procedure in step 1.

On successful completion of steps 2 or 3, the algorithm computes d_p and subsequently creates the appropriate $\{process, d_p\}$ tuple. We will now examine the specific features of this algorithm in relation to the life phase under consideration. Moreover, we will see some examples of matching tables and import spreadsheets for a better understanding of the above proceedings.

Construction phase An excerpt from the construction phase Excel matching table is given in Table 3.2 as an example; it features the ecoinvent matching for the ISAaR technologies "battery" – here referring to 1st life batteries – and "biomass-fired cogeneration unit". Two particularities can be highlighted in this excerpt. First, the ecoinvent process name for batteries is labeled as "import", meaning that a specific LCI

ISAaR technology key	ISAaR technology name	Ecoinvent process name	Ecoinvent unit	Ecoinvent generation capacity [MW]	Ecoinvent storage capacity [MWh]	Ecoinvent share in t_k
2	Battery	import	megawatt hour	–	1	1
6	Biomass-fired cogeneration unit	heat and power co-generation unit construction, 160kW electrical, components for electricity+heat	unit	0.16	–	0.73
6	Biomass-fired cogeneration unit	heat and power co-generation unit construction, organic Rankine cycle, 1000kW electrical	unit	1	–	0.27

Table 3.2 Excerpt from Excel matching table for assessing the power plant facilities' construction phase. This table is not extensive and serves for methodology illustration purposes only.

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, BESS, Li-ion	BESS, Li-ion	1	megawatt hour	DE	production
–	market for battery, Li-ion, NMC111, rechargeable, prismatic	battery, Li-ion, NMC111, rechargeable, prismatic	7021.28	kilogram	GLO	techno-sphere
Battery container	literature, BESS, battery container	BESS, battery container	0.81	unit	RER	techno-sphere
Power electronics container	literature, BESS, power electronics container	BESS, power electronics container	0.81	unit	RER	techno-sphere
Installation	literature, BESS, installation	BESS, installation	0.81	unit	RER	techno-sphere

Table 3.3 Example of a manual ecoinvent process creation table – here for batteries – for methodology illustration purposes.

for this process has been created by the user in a separate Excel spreadsheet; Table 3.3 displays this LCI. Through this table, we can also comment on the layout of the LCI import spreadsheet template. Indeed, for each exchange composing the LCI, the process name, its resulting product, its amount, its unit, and its location have to be indicated. A table clarifying all ecoinvent location acronyms used within this thesis is given in the Appendix in Table A.1. Furthermore, the type of exchange has to be specified; we distinguish three categories:

1. Production processes – which indicate what products result from the process;
2. Technosphere processes – which designate process inputs belonging to the transaction matrix A;
3. Biosphere processes – which describe elementary flow processes appertaining to the matrix B and accounting for direct interactions with the surroundings.

It is possible to nest imported LCIs in other Excel spreadsheets and reference the sheet's name in the first column. As a second peculiarity to Table 3.2, we can note that 73% of the biomass-fired cogeneration units produced by ISAaR use gas engine technology and 27% organic Rankine cycle technology; hence LCI_6 will be composed of two tuples, one corresponding to each technology. We further denote the share of a technical realization alternative corresponding to one ecoinvent process p as $share_p$. This factor helps to account for technological realization developments over time and may vary depending on the expansion year t_k.

Moreover, the matching file sets apart generation and storage power plant facilities by either referencing a generation capacity in MW or a storage capacity in MWh. This referenced value documents the plant capacity the ecoinvent process LCI setup was based on. Indeed, this is necessary for adjusting the ecoinvent process with the ISAaR technology, as, in a vast majority of cases, the ecoinvent facility construction LCI is given for the entire plant as a "unit". Dividing by this reference capacity thus enables obtaining an LCI corresponding to one unit – i. e. 1 MW or 1 MWh – of power plant construction. Multiplying this readjusted LCI with the ISAaR construction investment, we get an LCI for constructed capacity taken into operation in an expansion year. Let us denote the ecoinvent plant capacity as $P_{unit}^{(eco)}$, regardless of whether the value stands for a generation or storage capacity. It shall also be noted that this value does not change over time. Now, if we recall that the difference in gross constructed capacity for an ISAaR technology is designated as $P_{gross}^{(diff)}$, then the demand d_p for this ecoinvent process p in an expansion year $t_k \in \mathcal{E}$ and a region r is computed as follows:

$$d_p\left(t_k, p, r\right) = share_p\left(t_k, p, r\right) \frac{P_{gross}^{(diff)}\left(t_k, f, e, r\right)}{P_{unit}^{(eco)}\left(p, r\right)} \tag{3.13}$$

Use phase Analogously to the construction phase, a matching table excerpt for the use phase can be found in Table 3.4; it features the ISAaR technologies “biomass imports” and “natural gas imports”. We can see a few differences in its structure. First of all, the use phase matching table features a column called “Ecoinvent facility construction”. Indeed, within the use phase, we only assess the energy carrier provision and direct combustion impacts, whereas the manufacturing of adequate conversion facilities belongs to the construction phase and is thus the object of other considerations, as seen before. However, some of our selected ecoinvent processes for the energy carrier supply – and especially those involving the combustion of energy carriers – include the construction of facilities within their LCI as part of the life cycle perspective. The aforementioned column then serves to record the existence of such, in the scope of our assessment, undesired exchanges within the matching ecoinvent process. The framework then makes sure to exclude that exchange from the assessment by creating a copy of the matching process without the construction exchange featured in the column.

ISAaR technology key	**ISAaR technology name**	**Ecoinvent process name**	**Ecoinvent unit**	**Ecoinvent conversion factor**	**Ecoinvent facility construction**	**Ecoinvent share in t_k**
18	Biomass imports	market for biogas	cubic meter	158.38	–	1
19	Natural gas imports	natural gas, burned in gas turbine	mega-joule	3600	market for gas turbine, 10MW electrical	1

Table 3.4 Excerpt from Excel matching table for assessing the power plant facilities’ use phase. This table is not extensive and serves for methodology illustration purposes only.

Furthermore, compared to the construction matching table, the generation or storage capacity values have here been replaced by a conversion factor, which, in a similar fashion, serves to align the ecoinvent process unit with the ISAaR technology’s unit. Indeed, for all ISAaR energy carriers, results are given in MWh of supplied energy – except for CCS, where results are given in tonnes of offset CO_2 emissions. Yet, e. g., as indicated in Table 3.4, the ecoinvent process LCI assimilated to ISAaR biomass imports is given with respect to 1 m^3; hence, we need to convert m^3 into MWh. Accordingly, taking the lower heating value (LHV) for biogas as given by the ecoinvent process documentation of 22.73 MJ/m^3, we can compute that $\frac{3600\ \text{MJ/MWh}}{22.73\ \text{MJ/m}^3} = 158.38\ \text{m}^3\text{/MWh}$ of biogas are necessary for supplying an energy amount of 1 MWh. In general terms, we denote that conversion factor as $factor_{conv}^{(eco)}$, then, recalling the formula for computing the import amount of an energy carrier provision alternative attributed to the energy supply sector in Equation (3.12), we can determine the demand d_p in an expansion year $t_k \in \mathcal{E}$ and a region r as:

$$d_p\left(t_k, p, r\right) = factor_{conv}^{(eco)}\left(p, e_{alt}\right) \cdot share_p\left(t_k, p, r\right) \cdot share_{import}^{(ESS)}\left(t_k, e_{alt}, r', r\right) \sum_{r'} E_{import}\left(t_k, e_{alt}, r', r\right) \tag{3.14}$$

3.2.3 Impact Assessment

Having established the LCI of each ISAaR technology featured in the difference for each life phase, the impact score of the additional investments of each scenario can straightforwardly and, most importantly, automatically be calculated by the Brightway2 LCA software environment. Therefore, within the impact assessment step of our framework, all individual technology LCIs are gathered in one common LCI representing the additional investments of one scenario and, combined with the ecoinvent pLCI DBs previously set up, passed as input to the already fully implemented Brightway2 function for LCIA computation. All impact categories chosen by the user can be assessed in a single run using this function. The just described procedure corresponds to the "*compute_lca (lci, prospective_ecoinvent_dbs)*" function of the framework's sequence diagram in Figure 3.2. We can still say a few words about what happens within the function. Indeed, the Brightway2 function breaks down the input LCI into elementary process flows, to which it associates an impact indicator based on the assessed impact category; each impact category has its own characterization DB. For further details, we invite the reader to refer to Section 2.1.2.

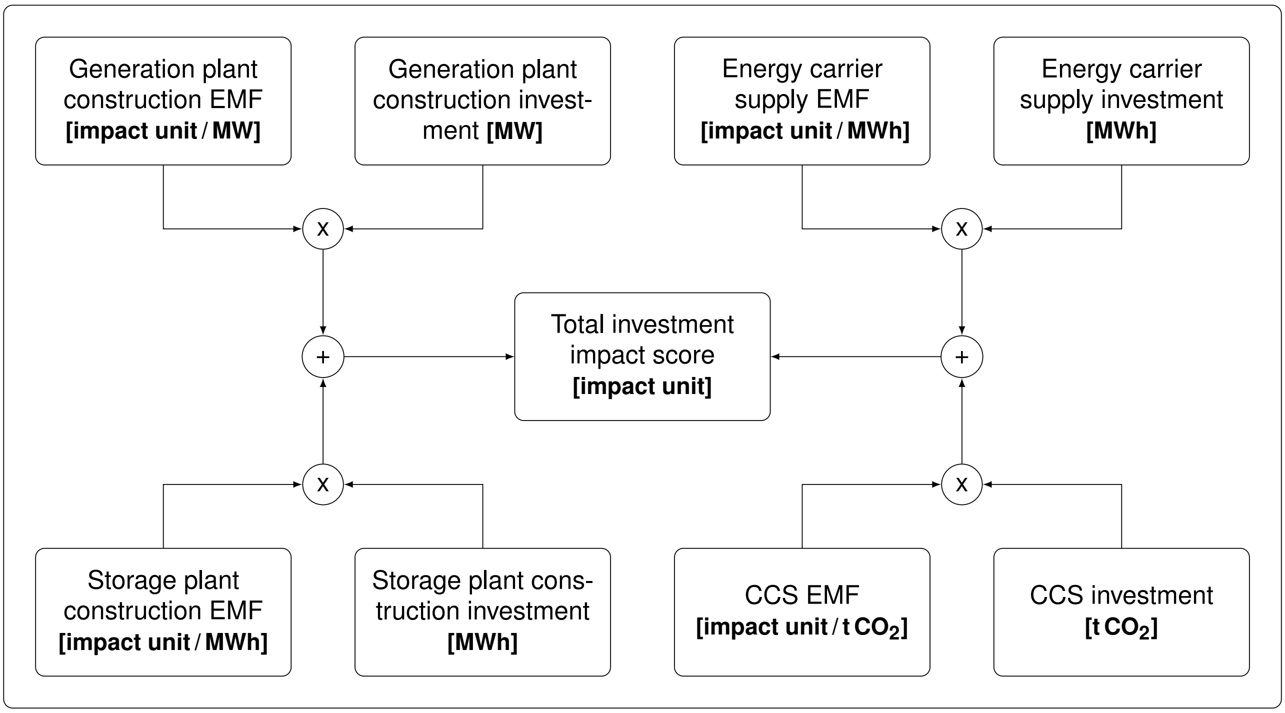

Figure 3.5 Alternative representation of the LCIA methodology applied in the framework

Figure 3.5 provides a more graphical representation of the applied LCIA methodology while taking on a slightly different explanation angle. In this representation, the life phase's environmental impacts are determined by taking each investment type's EMF[3] and multiplying it by the actual investment need. By tallying all thus obtained investment need impacts, we obtain the total additional investment impacts of a scenario and may confront both scenarios' results. In order to account for the evaluation of miscellaneous environmental impacts, the impact scores are expressed with respect to an unspecified "impact unit", which is to be replaced by the assessed impact categories' characteristic unit. The applied EMF for each ISAaR technology within the difference can be ascertained by modifying the demand d_p such that it reflects the provision of 1 MW of generation capacity (respectively 1 MWh of storage capacity) in the case of the construction phase and of 1 MWh of supplied energy (respectively 1 t of stored CO_2 for CCS) in the case of the use phase. In other words, regardless of the technology under investigation, the demand d_p should only comprise one unit of investment. Mathematically, if $d_p^{(EMF)}$ is the demand associated with one

---

[3] We define an EMF as being a representative value of a system's impact score per characteristic unit of that system. For the sake of example, we would most likely express the indicative impacts of any fuel with respect to 1 kg of that fuel. By multiplying this value with the mass of fuel needed for, e. g., driving 1 km, we would then get the fuel-related impacts for driving this distance.

ecoinvent process p for determining the EMF of an ISAaR technology, then, in the case of the construction phase, this value can be computed by modifying Equation (3.13):

$$d_p^{(EMF)}\left(t_k, p, r\right) = share_p\left(t_k, p, r\right)\frac{1}{P_{unit}^{(eco)}\left(p, r\right)} \tag{3.15}$$

and, in the case of the use phase, by modifying Equation (3.14):

$$d_p^{(EMF)} = factor_{conv}^{(eco)}\left(p, e_{alt}\right) \cdot share_p\left(t_k, p, r\right) \tag{3.16}$$

The EMF of any ISAaR technology can then analogously be obtained by applying Algorithm 1 with the adapted demand factor for each ecoinvent process.

3.2.4 Interpretation

As to the interpretation of the results, the framework does render some plots for visualizing differences in investments and impact scores between the scenarios if willed by the user; however, any inferences or recommendations have to be elaborated by the user himself. Thus, the framework has very little contribution to this step of the pLCA.

Chapter summary *In this chapter, we have presented the elaborated methodology for the conception of our automated framework for evaluating one measure's environmental impacts on the energy system. As a whole, the framework assesses all supplementary energy supply sector investments required for covering the energy demand in a given expansion year. These investments comprise the construction of generation and storage capacity as well as the supply and combustion of energy carriers for conversion purposes. To this end, the framework centralizes and manipulates information from four external entities for conducting the pLCA. We can especially cite the FREM DB for querying ISAaR scenario energy system results, the Microsoft Excel matching file for associating ISAaR technologies with ecoinvent processes, and the Brightway2 project for calculating impact scores.*

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4 Application of the Framework to Bidirectional Charging Strategies

In this chapter, we take on the role of user of the framework as opposed to its developer in order to investigate the thesis' superordinate objective – i. e. the assessment of the life cycle impacts on the energy system of the deployment of the flexibility option "bidirectional charging".

Goal and structure of the chapter *This chapter is a direct application of the framework methodology set up in Chapter 3. By conducting a pLCA on the energy system expansion difference induced by V2G policies, we aim to determine if such charging strategies might have an environmental advantage on the energy system in the future and, thus, investigate our second and third research questions. For this purpose, we will, as a first step, select scenarios mirroring this measure and, subsequently, make an inventory of each scenario's additional energy system investments. From this, we will be able to compute indicators of each scenario's impacts, which we will analyze and interpret in a final step.*

4.1 Goal and Scope Definition

The goal and scope definition of the framework in Section 3.2.1 has been set up to be compatible with any investigated measure and, consequently, any scenario under consideration. Due to this fact, all aspects of a comprehensive goal and scope definition cannot be covered, some being left to the appreciation of the user. We will address this voluntary shortcoming in the upcoming discussion. No amendments will be made to the generally specified framework goal and scope definition, solely further criteria will be clarified.

4.1.1 Scenarios

So as to accurately assess the flexibility option "bidirectional charging", it is primordial to choose ISAaR scenarios whose only difference is the deployment of such a measure. Only by ensuring this condition are we able to investigate the changes in the energy system purely induced by the measure. In the following, we will justify the selection of the scenarios we apply the framework on, as well as enunciate the assumptions these scenarios are built on.

Scenario selection In order to investigate the endogenous changes in the energy system brought forth by bidirectional charging strategies, we apply our framework to two ISAaR scenarios, which have been developed during a previous FfE study aimed at assessing the economic and ecological effects of flexibility options on the future energy system while especially highlighting the interactions between bidirectional BEVs and stationary 1st and 2nd life BESS. In the framework of this study, four scenarios were conceptualized as extensions of a reference scenario called *Start*. All scenarios represent a possible energy system expansion pathway towards reaching the climate targets of the European Green Deal (European Commission, 2019). The decisive factor of the baseline scenario *Start* is that it does not feature any stationary battery storage or V2G application for BEVs. Building upon *Start*, different storage options have been added in the four extension scenarios. One of them solely accounts for the expansion of stationary battery storage – i. e. 1st and 2nd life batteries – and is thus called *1st2nd*. The three other extension scenarios feature bidirectional charging strategies. The *V2G* scenario adds mobile BEV batteries as virtual power plants and storage that can be used as a flexibility option in the energy system. In *V2G+1st*, the use of 1st life stationary batteries is introduced as an additional option with respect to the *V2G* scenario. Finally, the

	Start	*1st2nd*	*V2G*	*V2G+1st*	*allST*
1st life batteries		✓		✓	✓
2nd life batteries		✓			✓
Bidirectional charging			✓	✓	✓

Table 4.1 Storage options featured in the ISAaR scenarios developed within the scope of a past FfE project

scenario *allST*, short for “all storage”, includes all flexibility options, i. e. V2G and 1st and 2nd life batteries, in its model. Table 4.1 summarizes the different storage options available in each scenario.

Recalling the objective of this thesis as given in Section 1.3, the scenarios selected within those listed above should reflect the difference bidirectional charging makes in the expansion of the energy system, hence, the only difference between the two chosen scenarios should be the presence of a V2G flexibility option. Looking at Table 4.1, this applies to the scenarios *Start* and *V2G* or *1st2nd* and *allST*. However, we consider a future energy system with RE integration without any battery storage technologies unlikely (Datta et al., 2021; Wali et al., 2021). As the scenario *Start* does not meet this criterion, we choose the scenarios *1st2nd* and *allST* as a basis for our comparison.

For applying our automated pLCA framework, we need to define the reference scenario and the altered scenario. Looking again at Table 4.1, *allST* has all the characteristics of the scenario *1st2nd* with an additional bidirectional charging flexibility option and thus represents an altered version of *1st2nd*. Consequently, *1st2nd* is our reference scenario, and *allST* is our altered scenario.

Preliminary Study As stated earlier, the examined scenarios have been created within the scope of a past FfE project with the purpose of investigating the ecological impacts of different BESS flexibility options. This raises the question of the contributions of our thesis with respect to this past FfE study. In short, the FfE project focused on the prospective hourly EMFs of the electricity generation for each scenario. Likewise to our framework, this study also accounted for future technology developments through *premise* and relied on ecoinvent for modeling background processes of ISAaR technologies. Only GWP impacts have been investigated. The preliminary study showed that, even if V2G might allow more peak shaving and thus smoothing of the GHG emissions, it does not make a huge impact on the pLCA-based electricity generation EMFs.

However, only the electricity production and the changes in BEV use induced by charging strategies have been taken into account in the system boundaries, meaning that e. g. the construction of new power plants or of BEV charging infrastructure have not been included in the scope of the life cycle contributions. Moreover, the generation of energy carriers other than electricity was not considered in this analysis. From a life cycle perspective, these factors might play a more decisive role in the environmental impacts of bidirectional charging applications with respect to stationary storage options. The contributions of this thesis with respect to this study are thereupon to broaden the system boundaries of the electricity generation system to cover the overall energy supply sector with a particular focus on including further energy carriers and assessing the construction of power plants. Furthermore, in our thesis, we shall go beyond the investigation of GWP impacts on the environment.

Scenario assumptions All of the scenarios cited above are based upon the model parameters and assumptions of the solidEU scenario of the FfE eXtremOS project (Guminski et al., 2021; Kigle et al., 2022), whose indicators and trends are shown in Figure 4.1. This scenario follows an EU socioeconomic pathway shaped by solidarity and cooperation. Thereby, the anthropogenic origin of climate change is generally accepted, and all EU governments are set upon significantly reducing GHG emissions. Regulations and incentives shall push Europe towards the protection of ecosystems, a more eco-friendly use of resources, and the integration of the EU electricity grid. An emission reduction target of 95% until 2050 with respect to 1990 levels, as proposed by the European Green Deal (European Commission, 2019), is sought within the scope of this scenario. The energy supply sector expansion is dominated by the integration of RES with a

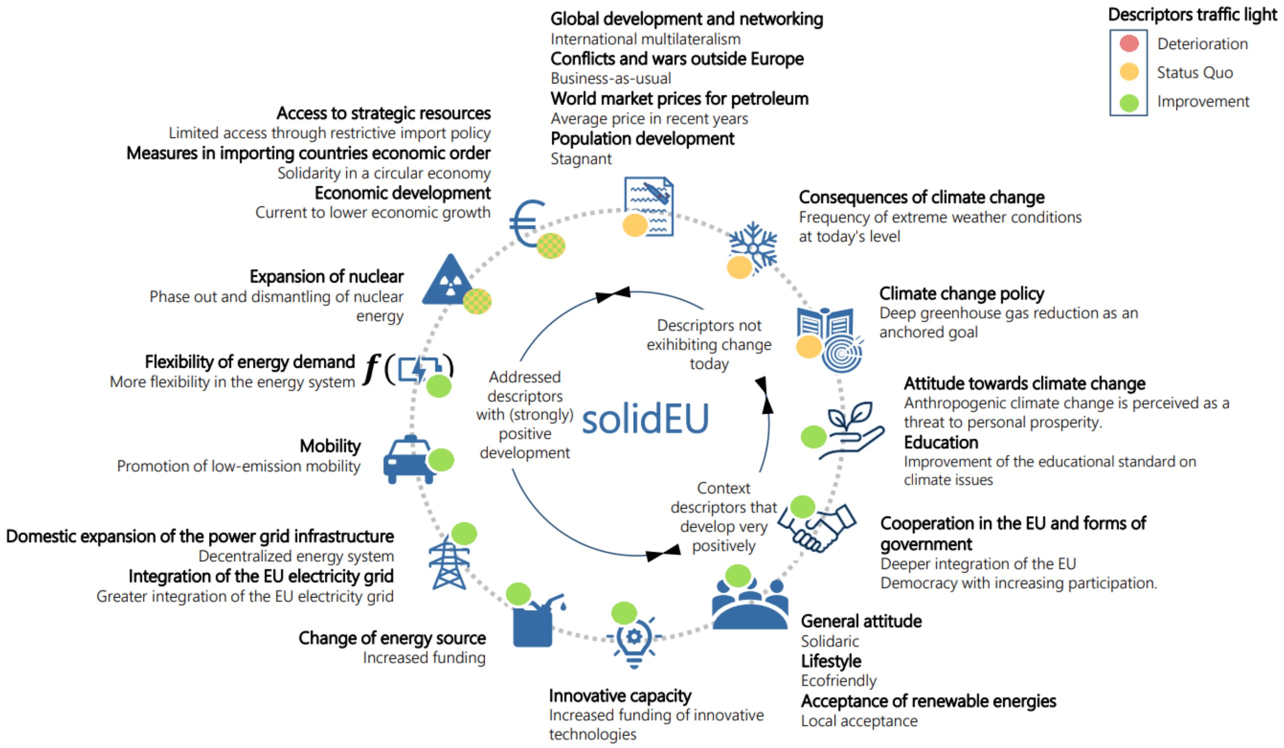


Figure 4.1 SolidEU scenario indicators and trends as in Guminski et al. (2021)

growing call for flexibility options and for coupling between energy carriers. While the climate targets may be achieved, this requires a significant effort. Outside of the EU, business-as-usual trends are assumed.

For an accurate estimation of future impacts, the technological trends and developments assumed for modeling the background processes of ISAaR technologies have to concur with ISAaR scenario trends. Returning to SSP and RCP considerations as introduced in Section 2.1.3, the selected IAM narrative for creating ecoinvent pLCI DBs should be in line with the just enunciated solidEU scenario pathway. While in this scenario, the EU features very ambitious climate mitigation targets, the rest of the world follows historical trends; hence, altogether, we tend more towards an SSP2 “Middle of the Road” pathway. We justify this decision by stipulating that even if products are used in an EU country, a significant share of their life cycle process flows can be assigned to other world regions and, thus, considering an SSP1 narrative within our pLCA would be too optimistic. Moreover, within the solidEU scenario, international climate policies are aligned on reaching the Paris Agreement climate targets of 1.5 °C. Yet, this RCP is not achievable in combination with the SSP2 course in the IAM REMIND (Riahi et al., 2017). In consequence, despite striving to comply with the Paris Agreement, we consider global surface temperature rises of 1.6-1.8 °C to be more realistic within our ISAaR scenario narrative, and, as a result, base our ecoinvent pLCI DBs on the RCP2.6 pathway. Recapitulating the above discussion, an SSP2 RCP2.6 IAM scenario shall be used for reflecting future considerations within the pLCA, in order to come as close as possible to the solidEU assumptions on a global level.

We will now take a closer look at the scenarios *1st2nd* and *allST* since these are the scenarios we are, in fact, interested in. In both scenarios, the underlying transport model is identical even though BEVs in *1st2nd* cannot perform bidirectional charging. Thus, one scenario’s ability to perform V2G is not influenced by the presence of registered BEVs in the model but rather by the exploitation of the available BEV fleet to V2G ends. Figure 4.2 shows the number of registered passenger cars common to both scenarios in future model evaluation years in Germany according to their fuel source. We can observe that the number of ICEVs is projected to decline in favor of BEVs over the years; by 2050, electric drives represent the most largely adopted technology solution. Other eco-friendly fuels, such as hydrogen, remain marginal in the

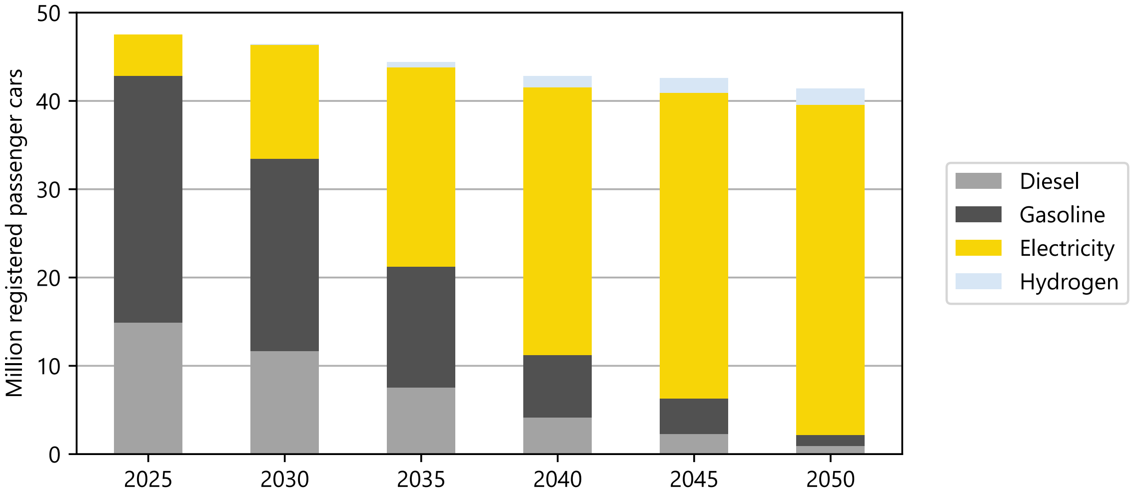


Figure 4.2 Projected number of registered passenger cars broken down by fuel source in Germany

overall balance. In the model, German aspirations of reaching 15 million registered BEVs by 2030 fall just short.

By default, in the ESM, all registered BEVs are assumed to be uncontrolled, yet for the *allST* scenario, these BEVs are eligible for an upgrade towards unidirectional or bidirectional smart charging. Each BEV may provide 70 kWh of storage capacity and is integrated into the energy system according to Kern and Kigle (2022). Thus, in contrast with *1st2nd*, BEVs in *allST* are capable of delivering meaningful storage potential to the energy system by means of a BEV-dominated passenger car fleet, as presumed by the transport model. Beyond the possibility of using BEVs for smart charging purposes in *allST*, all underlying ESM assumptions are identical between both scenarios – this applies to both scenario and model parameters. In particular, the energy system expansion is in line with German and international climate and energy policies in place; this includes regulations on carbon emissions, nuclear and coal-fired power plant dismantling, and grid infrastructure development. Moreover, RE expansion becomes an endogenous parameter as of 2035, while it is set exogenously until 2030.

4.1.2 Use-case Specific Considerations

Now that the ISAaR scenarios for evaluating the flexibility option “bidirectional charging” have been presented, the generic goal and scope definition of the framework shall be complemented to account for our use-case-specific considerations.

Temporal and geographical scope The temporal scope of the analysis follows the expansion years evaluated by the ESM ISAaR for the scenarios under consideration; in our case, this involves five-year steps starting from 2025 and ending in 2050. It is meaningful to include all those expansion stages in our analysis to account for the gradual cost-optimized system expansion pathway from nowadays to net zero emissions on an EU scale in 2050. One might argue over the realization feasibility of these scenarios, yet this is out of the scope of this thesis. To summarize, we cover the environmental impacts the deployment of V2G strategies would imply on an energy system complying with a Green Deal temporality.

As to the geographical scope of the analysis, we consider the projected German energy system expansion. Germany is a country striving toward a high share of fluctuating RE in their energy mix, which raises particular challenges concerning their integration. Providing sufficient flexibility through BESS is a necessary aspect of achieving this ambition, as highlighted in the motivation in Section 1.1. Hence, studying the potential advantages and drawbacks of different flexibility options is particularly relevant in this country. Environmental impacts associated with each technology might play a crucial role in decision-making on this matter. All in all, Germany is a pertinent geographical region for the analysis because of its dire need for BESS in the future if it wants to comply with its targets.

System boundaries Even though our system boundaries have been quite exhaustively defined within Section 3.2.1, some clarifications on bidirectional charging investments are in order. The widespread deployment of V2G regulations and infrastructure is a prerequisite for providing significant V2G potential. For a BEV to be capable of smart charging, the installment of additional information and communication technologies (ICT) to the charging infrastructure is required. Within the scope of this thesis, we align ICT prerequisites with Wohlschlager et al. (2022). Likewise to this study, we assume that bidirectional charging takes place in private households only, and neglect the possibility of operating this strategy through public charging infrastructure. Moreover, we hypothesize that each BEV providing storage capacity to the system is associated with one household with its own smart charging-capable infrastructure; this implies that charging infrastructures cannot be shared between households. These two restrictions are probably not representative of future states, yet contemplating them would imply complex use-case approaches that go beyond the time frame of the thesis.

Let us take a closer look at the additional ICT requirements for smart charging as enunciated by Wohlschlager et al. (2022) and legally defined by the German distribution system's standards on communication infrastructure. Each charging infrastructure equipped for smart charging should include intelligent metering system components and one wallbox. The intelligent metering system must be composed of two modern metering devices (mME) and one smart meter gateway (SMGW). As for the wallbox, V1G services principally operate with AC, while V2G services require power electronics for the conversion to DC. Table 4.2 recapitulates the ICT requirements for the charging infrastructure regarding all charging scenarios – uncontrolled charging, unidirectional controlled charging, and bidirectional charging. From this, additional ICT requirements for smart charging scenarios can be straightforwardly deduced. With respect to uncontrolled charging, charging infrastructure capable of performing V1G or V2G services is equipped with one additional mME, plus, for bidirectional charging, the AC wallbox is replaced by a DC wallbox. DC wallboxes are distinctive in that they necessitate far more material resources than AC wallboxes, conferring them a proportionally higher ecological footprint (Wohlschlager et al., 2022).

	Uncontrolled	**V1G**	**V2G**
mME (1)	✓	✓	✓
mME (2)		✓	✓
SMGW	✓	✓	✓
Wallbox (AC)	✓	✓	
Wallbox (DC)			✓

Table 4.2 ICT charging infrastructure equipment requirements for different charging scenarios as in Wohlschlager et al. (2022)

As part of the goal and scope definition, we shall now discuss how to integrate additional ICT requirements for smart charging within the system boundary. In general, we want to assess the supplementary investments of the incorporation of such strategies in the energy system. Hence, this includes all ICT required for smart charging in relation to an uncontrolled scenario, as enumerated above. We would like to point out that in order to assess the replacement of an AC wallbox with a DC wallbox, we consider the difference in impacts between both in our boundary; in other words, we subtract the AC wallbox impacts from the DC wallbox impacts.

In light of the identical BEV fleet in the *1st2nd* and *allST* scenarios, no additional investments associated with BEVs and BEV batteries are included within the system boundary for bidirectional charging. Still, V2G operation further decreases battery pack lifetimes due to an increased volume of charging cycles, even if some criteria, such as battery cell chemistry, temperature, and state of charge, might mitigate this aging process (Lehtola and Zahedi, 2019; Marongiu et al., 2015). Consequently, in order to extensively include additional investments brought forth by V2G strategies, ancillary battery aging conditions should be taken into account within the pLCA. However, we neglect this aspect within our system boundary due to the complex and parameter-dependent quantification of V2G-based battery aging.

Impact categories As the assessed impact categories are left to the appreciation of the user to be adapted to his individual use-case, we here elaborate on our decision in this regard. The following two impact categories will be investigated within the scope of this thesis: GWP and metal depletion (MDP).

GWP is an essential metric for quantifying potential anthropogenic impacts on global surface temperature levels and is, among others, adopted by the IPCC within their Assessment Reports (Shine, 2009). Indeed, as illustrated by the ReCiPe endpoint indicator methodology, global warming has noteworthy impacts on human health and ecosystems in the long term because of the phenomena – extreme weather events, rising sea levels, etc. – brought forth by surface temperature rises. Therefore, the critical repercussions at stake make GWP a category worth studying. Impacts related to this category are expressed in CO_2-eq – here, we consider a 100-year time horizon. In practice, we apply the “IPCC 2013 no LT, climate change, GWP 100a” ecoinvent impact category as our method of choice for evaluating GWP impacts.

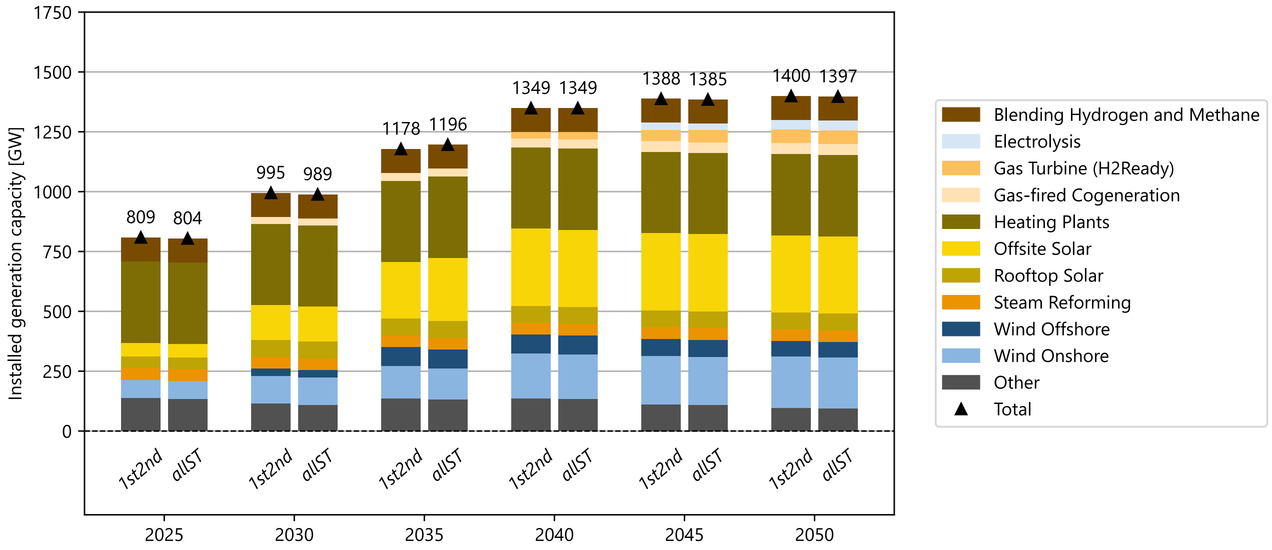
Now, let us justify the choice of investigating MDP repercussions in the pLCA. As seen in the motivation, one of the key aspects of V2G strategies resides in the dual use of BEV batteries, thus avoiding the need to manufacture supplementary battery cells for stationary BESS provision. Battery cells require a vast amount of raw metals for their production process (McManus, 2012; Oliveira et al., 2015), among which most are featured on the European Commission’s list of critical raw materials (European Commission, 2023). Depending on the considered battery cell chemistry, this principally includes lithium, nickel, cobalt, and manganese. Yet critical raw materials are classified as such because they are indispensable in today’s economy and, at the same time, are subject to a high supply risk; hence, a shortage of those materials might have great repercussions on the industry. Moreau et al. (2019) showed that proven metal reserves are insufficient for meeting the worldwide metal requirements of RE integration through 1^{st} life storage capacity in the future. Hence, in light of the resource cost stationary 1^{st} life batteries might have on modern society, we consider it relevant to see if other BESS flexibility options, such as V2G, might be advantageous in this regard. The impact category “MDP” enables the quantification of dissipative metal resource flows (Charpentier Poncelet et al., 2022) and is expressed as an equivalent of iron – denoted as Fe-eq. Concretely within the LCA software environment, we use the “ReCiPe Midpoint (H) V1.13 no LT, metal depletion, MDP” impact category.

4.2 Inventory Analysis

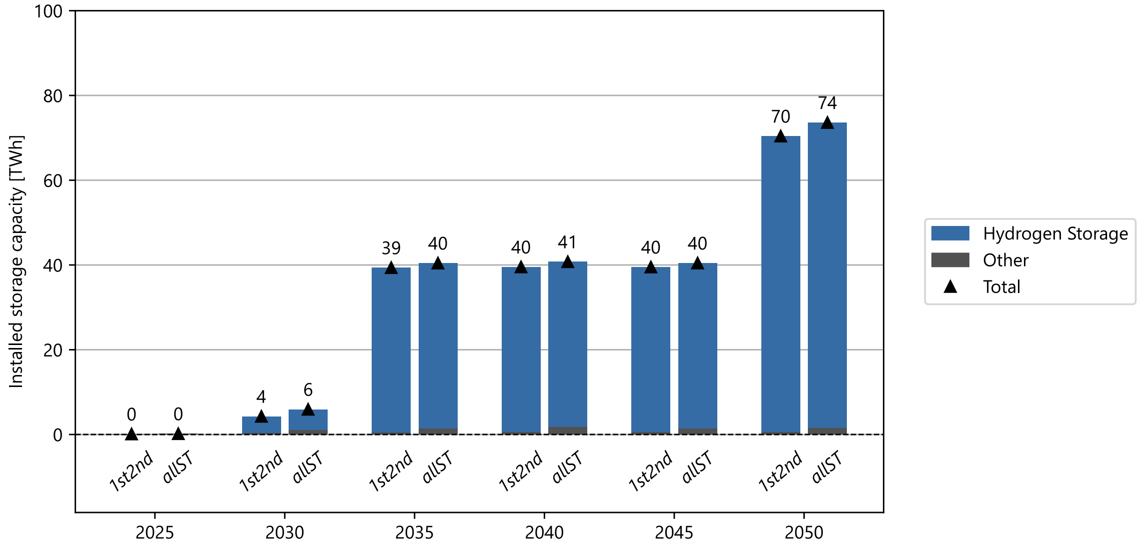
Within the scope of the framework application to the measure “bidirectional charging”, an inventory of the additional investments comprised in the system boundaries for each evaluated scenario is automatically compiled. The computation is performed in accordance with the inventory analysis methodology of Section 3.2.2. In the following, we will present and analyze the investment divergences between the *1st2nd* and *allST* scenarios as part of the pLCA of the energy system expansion induced by a V2G deployment; the construction and use phases will be treated separately.

4.2.1 Construction Phase

Installed capacity comparison The overall installed energy system capacity is the only ISAaR model result prerequisite for the computation of the additional capacity taken into operation between two scenario years. Figure 4.3 shows the *1st2nd* and *allST* scenario results for this parameter for all expansion years until 2050; thereby, results are broken down by facility type and differentiated between generation and storage plants. We would like to point out that in this representation, only the most prominent energy provision technologies are displayed separately; technologies with less weight in the overall balance are aggregated in the category “Other”. Two aspects of this figure are particularly interesting to examine: 1) the



(a) Installed generation capacity



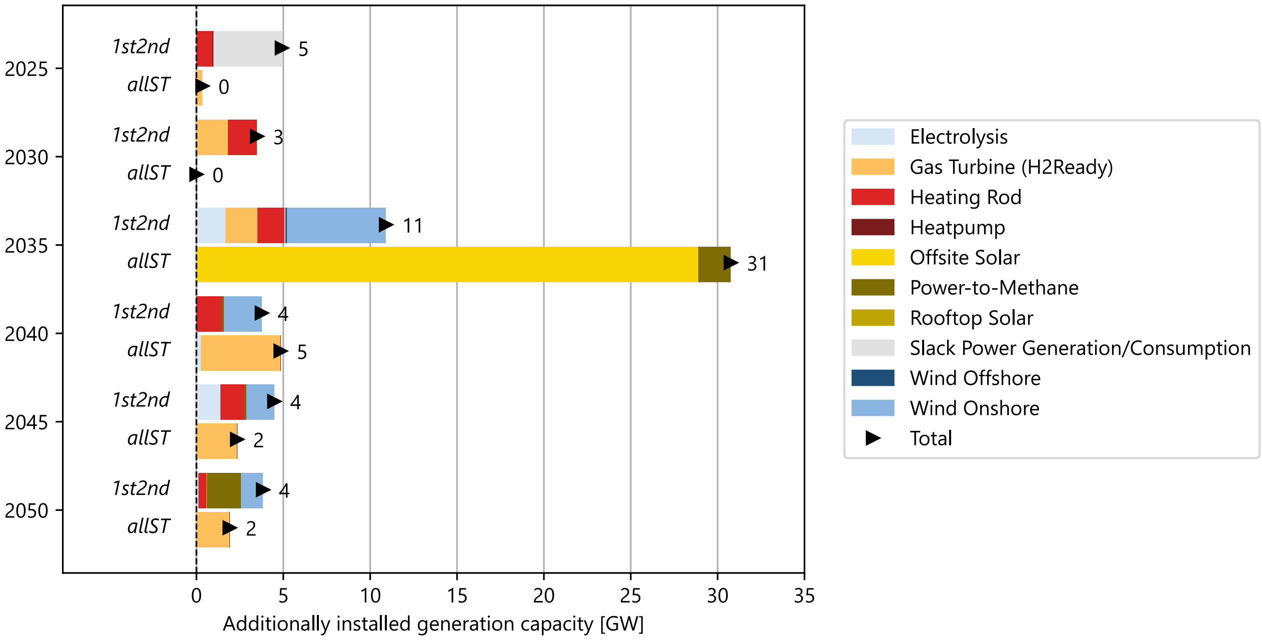
(b) Installed storage capacity

Figure 4.3 Comparative inventory of the overall installed capacity in the *1st2nd* and *allST* scenarios

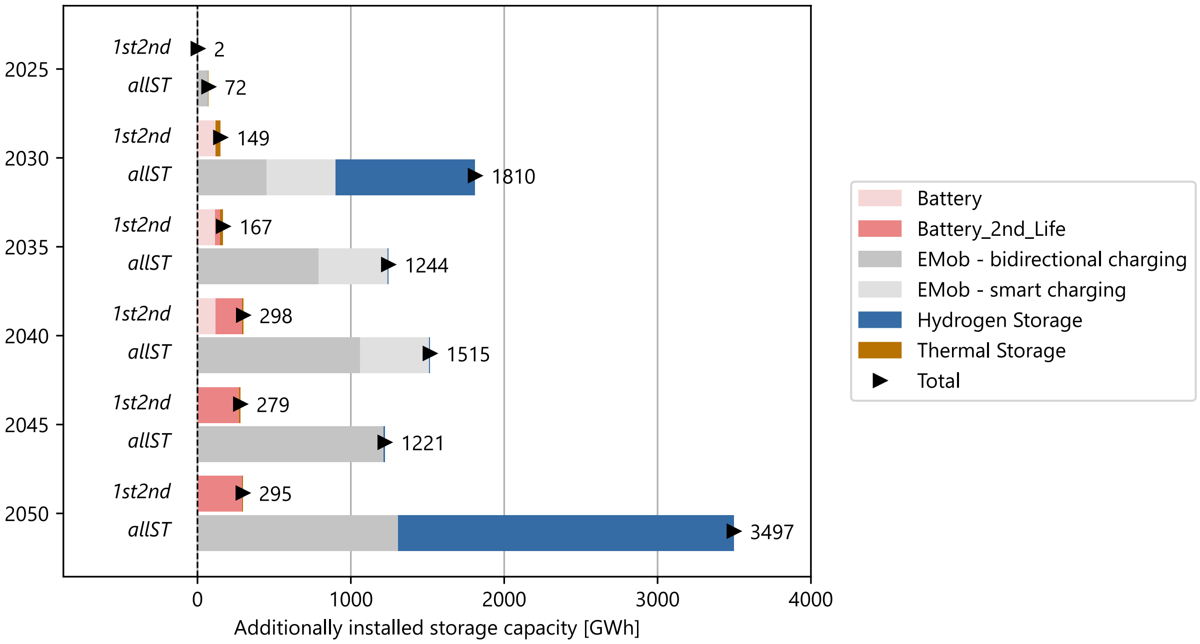
weight of individual facility types in the overall installed capacity balance and 2) the disparities between the two scenarios.

Let us start with the former. We can observe a major expansion of variable RE – offsite and rooftop PV, as well as offshore and onshore wind – in the overall generation balance in Figure 4.3a. In line with the government's road map, this makes RES the most prominent vector for energy provision in Germany by 2050 and a major pillar towards a successful energy transition. We can explain their proportionally large installed generation capacity with respect to other facility types by their distinctive fluctuations in availability, making it necessary to provide a higher overall generation potential. Besides, an increased contribution of PV capacity with respect to wind capacity can be observed due to improved integration of day-night solar presence through BESS-based peak shaving (Nykamp et al., 2013) with respect to less predictable wind availability variations. On the other hand, a relatively small amount of peak-load capacity is provided by gas turbines, as the successful integration of RES through BESS-based peak shaving reduces the need for such power plants, whose capacity is only used for a few hours a year. Moreover, a majority of the newly installed capacity in the evaluated expansion years contributes to the electrification of the German energy system, making electricity, biomass, and hydrogen essential energy carriers in the FEC (Guminski et al., 2021).

Regarding the installation of storage capacity in Figure 4.3b, we can see that hydrogen storage is projected to yield the vast majority of overall capacity. Battery-based flexibility options, as our main point of interest, do not even appear in the figure. This is due to the kind of storage provided by both options: BESS contributes to short-term electricity storage, whereas hydrogen storage constitutes a long-term storage option. Thereby, long-term storage serves to store large amounts of energy for future use, e. g. in the opposing season, while short-term storage provides fast flexibility to compensate for immediate energy



(a) Installed generation capacity disparities



(b) Installed storage capacity disparities

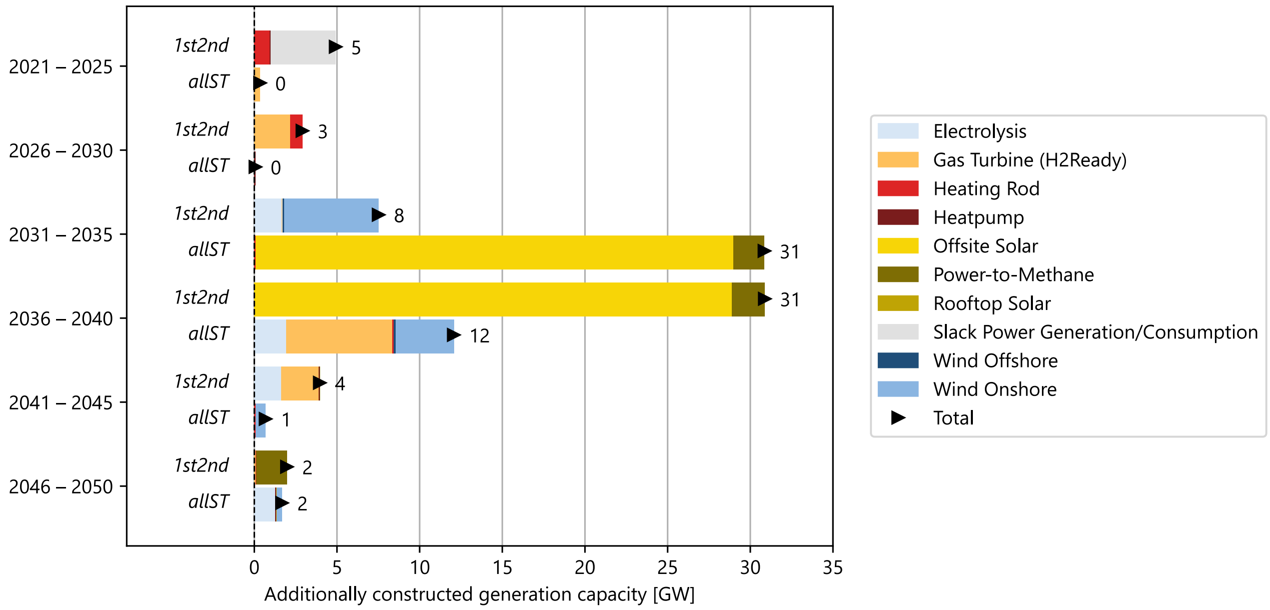
Figure 4.4 Inventory of the additionally installed overall capacity in the *1st2nd* and *allST* scenarios with respect to the other scenario availability fluctuations. For this reason, a more voluminous overall storage capacity must be installed in the case of long-term storage options.

Comparing the installed capacity for both scenarios, it is particularly noteworthy that, at first sight, very few differences prevail between *1st2nd* and *allST*. Indeed, the total installed capacity amounts are fairly similar between the two scenarios in all expansion years; totals only diverge by a few GW of installed generation capacity, respectively TWh of installed storage capacity. Moreover, on the whole, the deployment of bidirectional charging strategies does not induce any fundamental differences in the weight of individual plant types in the overall installed capacity balance. Most disparities cannot be seen within this representation as they only represent a small portion of the total installed capacity. From this, we can conclude that the chosen flexibility option does not have a significant influence on the model's endogenous system expansion. An analysis of the difference in installed capacity is necessary in order to highlight the divergences between both scenarios.

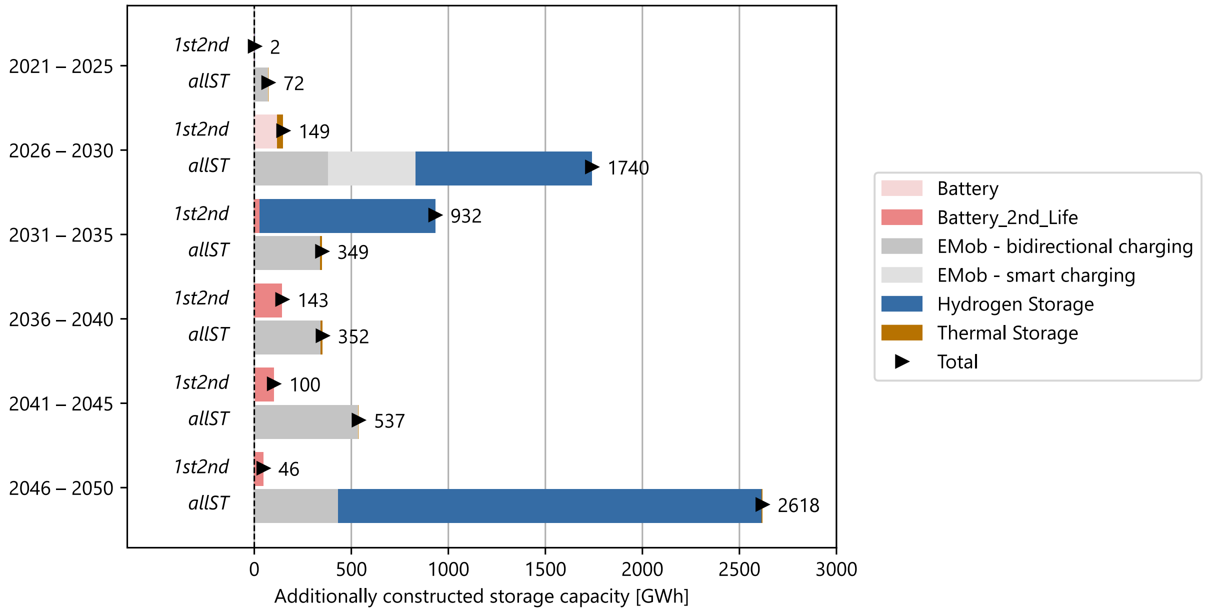
Installed capacity difference Figure 4.4 illustrates the annual difference between the two scenario bars of Figure 4.3. Disparities are positively attributed to the scenario they originate from – e. g. if more PV capacity is installed in *1st2nd*, then this additional capacity is assigned to the divergence inventory of this scenario. Furthermore, it shall be noted that they are not representative of actual capacity construction differences; on the contrary, should a facility type appear in the balance in an expansion step but not in the next one, then this difference may have been compensated by an equivalent capacity construction in the next expansion year in the other scenario.

On the whole, as predicted earlier, disparities are of small magnitude with respect to the overall installed capacity. Indeed, for generation capacities, disparities have an order of magnitude of 10^1 GW, whereas the overall installed capacity is on the order of 10^3 GW. They are, for the most part, attributable to the ISAaR model system cost optimization due to a higher flexibilization conferred by BEVs in relation to stationary BESS, as we will see in the upcoming discussion. As we recall, this merely represents the difference in installed capacity and not in constructed capacity, which is why interpretation approaches will only be given in the upcoming evaluation of the latter. Disparities in the installed storage capacity are more interesting to analyze, even though they are not very significant with respect to the overall installed capacity either. Indeed, the major divergence lies in the expanded flexibility option as brought forth by the scenario assumptions. Thus, in *1st2nd*, only 1^{st} and 2^{nd} life batteries are installed, whereas in *allST*, smart charging is mainly employed as a flexibility option. From this, we can conclude that even though *allST* has the possibility to install 1^{st} and 2^{nd} life batteries, the model favors BEV-based flexibility provision. We explain this favoring by an economical advantage of V2G services over stationary batteries since the model optimization is based on reducing system costs. Likewise, 2^{nd} life batteries are preferred over 1^{st} life batteries in *1st2nd*. We can further highlight that, due to the variable availability of BEVs, more overall smart charging capacity needs to be provided by mobile BEVS to compensate for the permanent readiness of stationary batteries. In ISAaR, a worst-case scenario of 60% BEV availability for bidirectional charging purposes is presumed. Thus, even in the worst case, the available installed storage capacity of BEVs in *allST* is larger than the installed storage capacity of stationary BESS in *1st2nd*: BEVs provide greater flexibility in the system. Furthermore, we can explain the occurrence of unidirectional charging storage capacity in Figure 4.4b by the fact that this technology enables load shifting.

Constructed capacity difference As stated by the goal and scope definition in Section 3.2.1, in the scope of the pLCA, the additional investments of each scenario are to be quantified, which, in the case of the construction phase, amounts to the additionally constructed capacity. The theory behind this calculation has been presented in Section 3.2.2.1 in the paragraph associated with the construction phase. There, it has been concluded that this computation only requires the difference in overall installed capacity, as shown in Figure 4.4, and the lifetime of different power plant types as input. The lifetimes associated with each ISAaR technology featured in the difference are given in the Appendix in Table A.2. Figure 4.5 portrays the results of this computation, i. e. the additional capacity taken into operation between two time steps in each scenario with respect to the other scenario; the reference zero value represents the baseline



(a) Constructed generation capacity disparities



(b) Constructed storage capacity disparities

Figure 4.5 Inventory of the additionally constructed capacity in the *1st2nd* and *allST* scenarios with respect to the other scenario

capacity identically constructed in both scenarios. In light of our research questions, it is important to note that results associated with *allST* represent additional investments induced by the deployment of bidirectional charging strategies, while results attributed to *1st2nd* indicate investments that can be saved by this measure. Exact values for *1st2nd* are given in Table A.18 and for *allST* in Table A.20 of the Appendix. Here, results are specified for an entire time step, yet in the upcoming impact assessment, the constructed capacity is evenly distributed between the years comprised within that step.

For the additionally constructed generation capacity in Figure 4.5a, we can see a time shift in the capacity expansion between both scenarios for most of the featured power plant types. However, on the whole, the amount of capacity taken into operation is almost identical for both scenarios. This time shift can be explained by the system cost reduction with which model results are optimized. This is especially true for offsite PV and onshore wind, where the highest disparities can be observed. Indeed, in general, it is beneficial for the model to use battery-based storage in combination with PV electricity provision, as it is cheaper than wind and its fluctuations are more predictable. Yet, as, due to the large-scale V2G application, a higher storage potential is available to the system in *allST*, it is worth investing in PV at an earlier stage in this scenario.

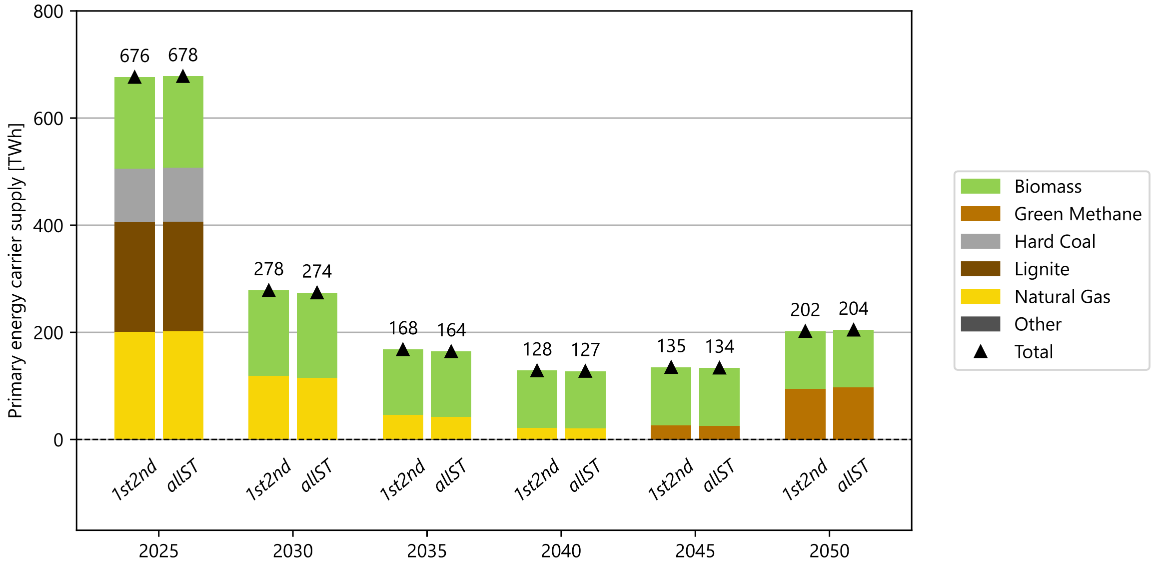
The results in the additionally constructed storage capacity difference (Figure 4.5b) confirm our previous inferences from Figure 4.4. In the case where V2G services are deployed, the supplementary manufacture of 1st life batteries can be saved in early time steps and of 2nd life batteries in later time steps. This time shift is due to the potential in 2nd life battery provision available to the model. Indeed, the technology can only be applied on a large scale in later years when enough BEV batteries have reached an advanced stage of life and are available for repurposing (see passenger vehicle transport model in Figure 4.2). 2nd life batteries then become more attractive to the model than 1st life batteries because of their lower cost (Hossain et al., 2019). On the other hand, in the case where bidirectional charging strategies are integrated into the system, the potential of BEV-based storage capacity is fully exploited by the model. Lastly, in that same event, we can observe an additional investment in hydrogen storage in 2050, which is not compensated in another time step in *1st2nd*. We might explain this difference in constructed capacity by the higher flexibility offered by V2G, which enables the production of a higher amount of hydrogen in cost-advantageous times. Hence, a slightly larger hydrogen storage capacity must be provided to store this ancillary hydrogen.

Matching with ecoinvent Having established the inventory of additional construction investments for each scenario, we can now proceed with matching the ISAaR technologies featured in the difference with ecoinvent processes as defined in Section 3.2.2.2. The matching table for those technologies can be found in Tables A.3, A.4, and A.5 of the Appendix. Share specifications are in line with ISAaR model parameter assumptions. We comment on certain table entries in the following:

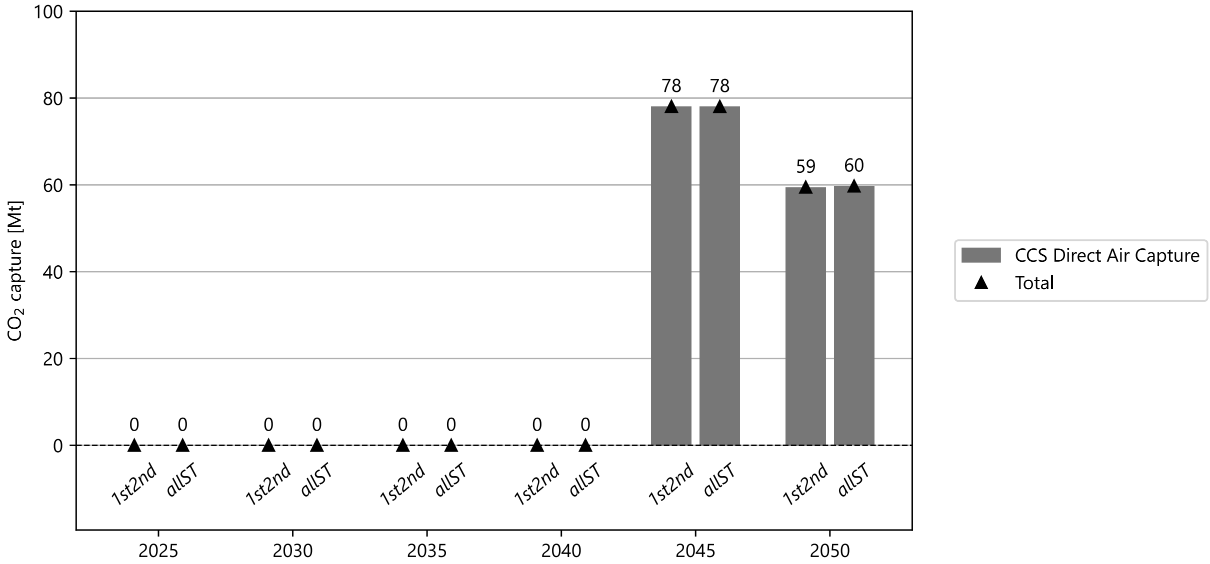
- ISAaR model investments in smart charging are associated with additional ICT requirements for the BEV charging infrastructure according to the use-case specific system boundary discussion in Section 4.1.2. As no ecoinvent processes already exist for these ICTs, we import data from literature. The LCIs for mME, AC wallbox, and DC wallbox are modeled according to Wohlschlager et al. (2022) and are given in Tables A.7, A.8 and A.9 of the Appendix respectively. The Excel import sheet synthesizing additional ICT requirements for V1G services, as used in the scope of practical framework application, can be found in Table A.10, and the one for additional requirements for V2G services can be found in Table A.11. As stated earlier, we associate one charging infrastructure with one BEV, each having a smart charging potential of 70 kWh according to ISAaR. Hence, all of the just enunciated requirements are supplementarily manufactured for every 70 kWh of provided BEV-based storage capacity.
- BEV battery repurposing into stationary 2nd life batteries is modeled based on the LCI in Schulz-Mönninghoff et al. (2021). The study considers a lithium-ion battery chemistry, as well as an application in Germany, and hence complies with our system boundary and ISAaR requirements. The LCI for the manufacture of stationary 2nd life batteries takes into account the BEV battery repurposing process (Table A.12) as well as the production of a battery container (Table A.13), a power electronics container (Table A.14) and their installation (Table A.15), thus comprising all additional investments needed for using this technology from as energy system's perspective. The Excel import sheet for 2nd life batteries in Table A.17 consolidates these individual investments.
- We proceed similarly for 1st life batteries. In effect, even if various ecoinvent processes exist for the manufacturing of battery packs, none include the necessary infrastructure for making it a fully functional stationary BESS. Hence, we combine the LCI for 2nd life BESS, as given in Schulz-Mönninghoff et al. (2021), with a battery pack manufacturing LCI already contained in the DB. Concretely, we assume that 1st life stationary batteries require the production and installation of battery and power electronics containers in the same way as 2nd life batteries; for consistency reasons, we use the same import processes as given in Tables A.13, A.14 and A.15. To account for the manu-

facturing of lithium-ion battery packs, we use the ecoinvent process called “market for battery, Li-ion, NMC111, rechargeable, prismatic” based on Dai et al. (2019). We justify this choice by the fact that this battery chemistry is widely used in BEV storage systems (Camargos et al., 2022) and that its GWP impact score is in accordance with the average for this type of chemistry determined by Peters et al. (2017). The Excel import sheet for 1st life batteries resulting from this deliberation can be found in Table A.16.

- The construction difference between both scenarios in Figure 4.5 includes an ISAaR technology called “Slack power generation/consumption”. This is a generic facility type used by ISAaR for balancing electricity generation and consumption within the energy system. Since it can be associated with no particular technology, we neglect it in our analysis; indeed, assumptions in this regard may falsify results.



(a) Imported energy carriers



(b) CO_2 capture

Figure 4.6 Comparative inventory of the overall energy carrier transactions allocated to the energy supply sector in the *1st2nd* and *allST* scenarios

- We could not find any accurate process for the construction of underground hydrogen storage either in ecoinvent or in literature. This lack of information in this regard has also been highlighted by Wulf et al. (2018) and is probably due to the fact that hydrogen storage is an emerging technology with very few large-scale applications yet. A literature search on the construction of underground gas storage facilities as a potential replacement technology likewise yielded no results. Thus, we settle on the use of the ecoinvent process for the construction of adiabatic compressed air energy storage underground plants as a substitute for underground hydrogen storage. For this reason, we cannot guarantee the accuracy of pLCA results concerning the environmental impacts of hydrogen storage.
- Given the time constraints associated with the realization of this thesis, we used some generic ecoinvent processes for all facility types not mentioned yet. Consequently, results associated with these processes may deviate from reality, as they do not exactly correspond to the actual technological developments and implementations of ISAaR.

4.2.2 Use Phase

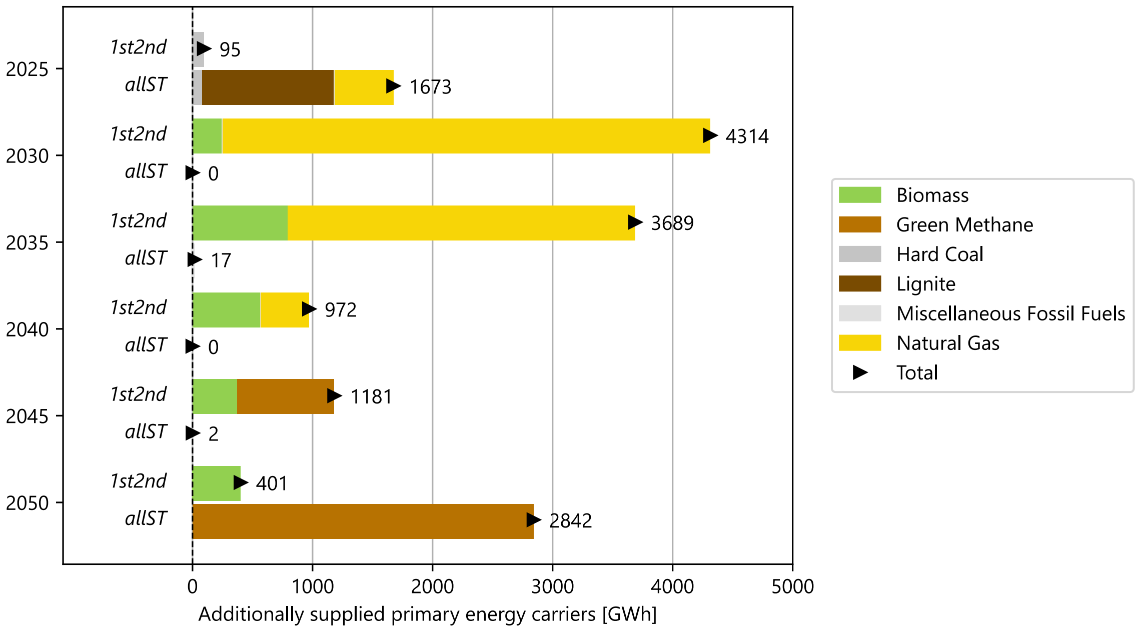
Energy carrier conversion We proceed analogously for the appraisal of the use phase investments as defined by the framework goal and scope definition in Section 3.2.1. Figure 4.6 provides a comparative illustration of the ISAaR results for both scenarios in this regard. Specifically, Figure 4.6a illustrates the supply in primary energy carriers required by the energy supply sector for conversion purposes and computed following the methodology enunciated in Section 3.2.2.1 in the paragraph related to the use phase. Figure 4.6b then portrays the use of CCS for meeting national and international climate targets

Likewise to the comparative inventory of the overall installed capacity, no significant differences between the *1st2nd* and *allST* scenarios can be observed. Indeed, the total amount and distribution of imported energy carriers only vary by a few TWh. We can, however, note that, in general, fossil imports are gradually replaced with green alternatives: from 2045 onwards, green methane is preferred to natural gas. Biomass is steadily imported over all expansion years and constitutes one of the major energy carrier requirements of the system. Lignite and hard coal-fired power plants are shut down in accordance with German regulations. Some other energy carriers, such as oil and green synthetic fuel, are also supplied to the system but are not visible in Figure 4.6a due to their relatively low import amounts. Furthermore, the model resorts to CCS in 2045 – which is the year in which Germany aspires to reach carbon neutrality – and in 2050 – the year in which net zero emissions shall additionally be achieved in the EU. Again, in both scenarios, nearly the same amount of CO_2 needs to be captured to comply with regulations.

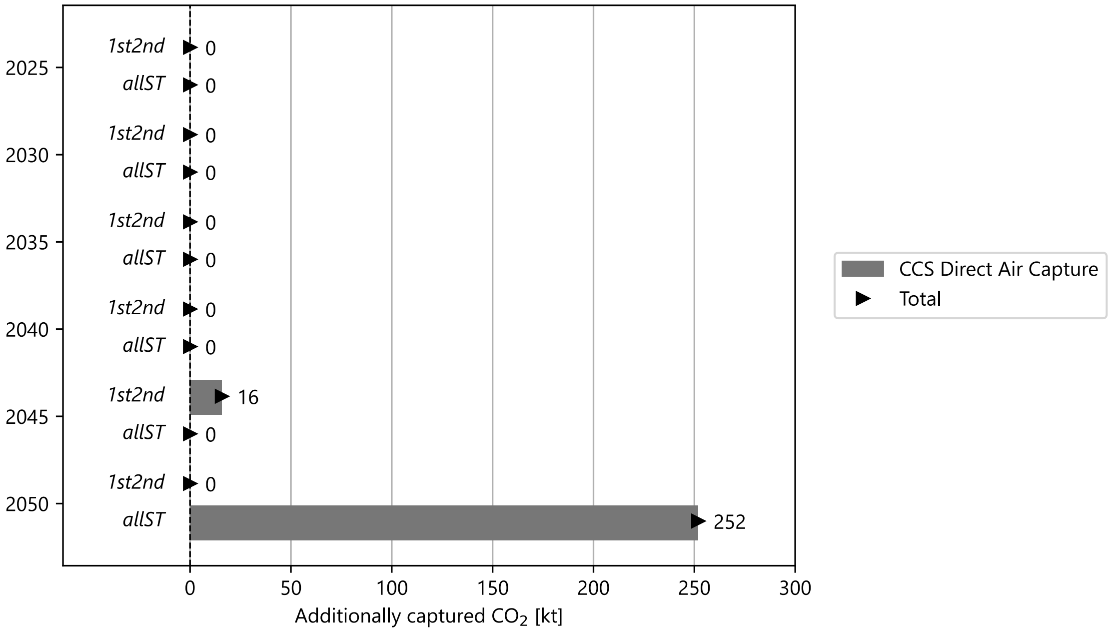
Energy carrier conversion difference The use phase divergences between both scenarios are shown in Figure 4.7. The visible differences only represent about a hundredth of the overall supplied energy carrier amount. It appears that, except in 2025, the deployment of V2G strategies will slightly reduce natural gas and biomass imports. On the other hand, it requires a marginally higher supply of lignite in 2025 and of green methane in 2050. We speculate that these variations are due to cost optimization differences in the model; however, a profound interpretation of these divergences lies beyond the scope of this thesis. Furthermore, in total, 236 kt of CO_2 are additionally captured in a bidirectional charging context. This slightly higher utilization of CCS can be explained by a lower resort of the industry sector to CCU.

Matching with ecoinvent Analogously to the construction phase, we match ISAaR technologies featured in the use phase divergences elaborated above with ecoinvent processes according to the methodology defined in Section 3.2.2. The matching table for this life phase is given in Table A.6 of the Appendix. In cases where it is relevant, LHVs used for adjusting units and determining the conversion factor are taken from the respective ecoinvent process documentation (see example for biomass in Table 3.4). Again, let us comment on certain process matches individually:

- Due to the fact that ISAaR does not specify the origin of primary energy carrier imports, we choose region-unspecific global ecoinvent processes for their provenance matching. This holds for all energy



(a) Imported energy carrier disparities



(b) CO_2 capture disparities

Figure 4.7 Inventory of the additional energy carrier transactions allocated to the energy supply sector in the *1st2nd* and *allST* scenarios with respect to the other scenario

carriers for which we do not assess the combustion – i. e. for biomass and green methane imports. For energy carriers, where the combustion is accounted for, processes for Germany or Europe are prioritized.

- As required by our system boundary, the combustion of fossil energy carriers must be included in the LCI. In our case, this holds for lignite, hard coal, natural gas, and miscellaneous fossil fuels and can be done via a selection of ecoinvent processes corresponding to the combustion of a given amount of primary energy carrier. Thanks to the life cycle approach, the upstream processes leading to the provision of the energy carrier are comprised in the ecoinvent process LCI and do not need to be accounted for separately. As this, however, also includes the construction of an appropriate facility for energy conversion, the corresponding upstream flow is voluntarily excluded from the assessment of the use phase as discussed in Section 3.2.2.

- Diesel has been selected for representing the generic ISAaR category “miscellaneous fossil fuels”.
- Ecoinvent processes for the import of methane do exist, yet they do not meet the “green” ISAaR technology requirement, i. e. they are not necessarily produced using green hydrogen[1]. Hence, in our assessment, we adapt these processes to meet this condition. For this purpose, we created a new ecoinvent process for green hydrogen based on an existing electrolysis hydrogen production process and replaced the unspecified electricity mix with the same electricity amount obtained to 50% from PV panels and to 50% from wind turbines. We then replaced the hydrogen flow of the ecoinvent process for methane production with our newly created green hydrogen process.
- As for the “CCS direct air capture” ISAaR technology, adequate processes are created by *premise* in the prospectively adapted ecoinvent LCI DBs. However, due to a disparity in the characterization of impacts between our chosen LCIA methodology and the one expected by *premise*, we need to adapt the exchange associated with the amount of CO_2 extracted from the atmosphere.

4.3 Impact Assessment

Based on the established LCI, the framework automatically performs the LCIA step of the pLCA according to the methodology in Section 3.2.3. Thereby, the ecoinvent background processes of an ISAaR technology comprised in the LCI are adapted to the expansion year in which this technology disparity was identified – e. g. should a technology feature in the disparities between both scenarios in 2040, then the background processes for this technology are modeled and assessed based on the ecoinvent DB generated by *premise* for 2040. As defined in the system boundaries, we investigate GWP and MDP impacts within the scope of our pLCA. Again, we address construction and use phase impact results separately.

4.3.1 Construction Phase

Emission factors Leaning on the alternative representation of the LCIA calculation step in Figure 3.5, we can, as a first step, determine the prospective impacts of the construction of one unit of each technology featured in the LCI to highlight which unitary technology expansion is especially harmful to the environment. In other words, we can compute each technology’s EMF in every assessed expansion year. This does, however, not spotlight which technologies will be particularly impactful within the scope of our differential pLCA, as this depends on the projected capacity construction. Figures 4.8 and 4.9 illustrate the EMFs for the impact categories GWP and MDP of the generation and storage technologies featured in the construction divergences between both scenarios as given in Figure 4.5. Thereby, for all technologies, their respective EMFs are given for all expansion years independently of their occurrence in the disparity LCI of individual years. Moreover, total value amounts have no meaning in this figure, individual technology EMFs have solely been stacked for the sake of visualization.

First and foremost, we can note that a vast majority of the observable EMFs tend to decrease over the expansion years hence mirroring an improvement of technological solutions and efficiencies. For the generation technologies in Figure 4.8, we can observe that per GW of constructed capacity, RE facilities – i. e. offsite and rooftop PV as well as onshore and offshore wind – have higher EMFs than other technologies. This is, among others, due to the diffuse characteristic of RES, meaning that several hundred wind turbines or solar panels need to be constructed to supply the same amount of capacity as a single conventional power plant. On the other hand, such facilities require a significant amount of polluting raw materials for their manufacturing – this includes, among others, silicon for PV modules and steel and concrete for wind turbine foundations (Hengstler et al., 2021). Looking at the MDP impact category specifically (Figure 4.8b), we can observe that among the RE facilities, rooftop PV panels have an even higher impact on metal resource availability. We explain this by the lower efficiency of rooftop PV plants with respect to

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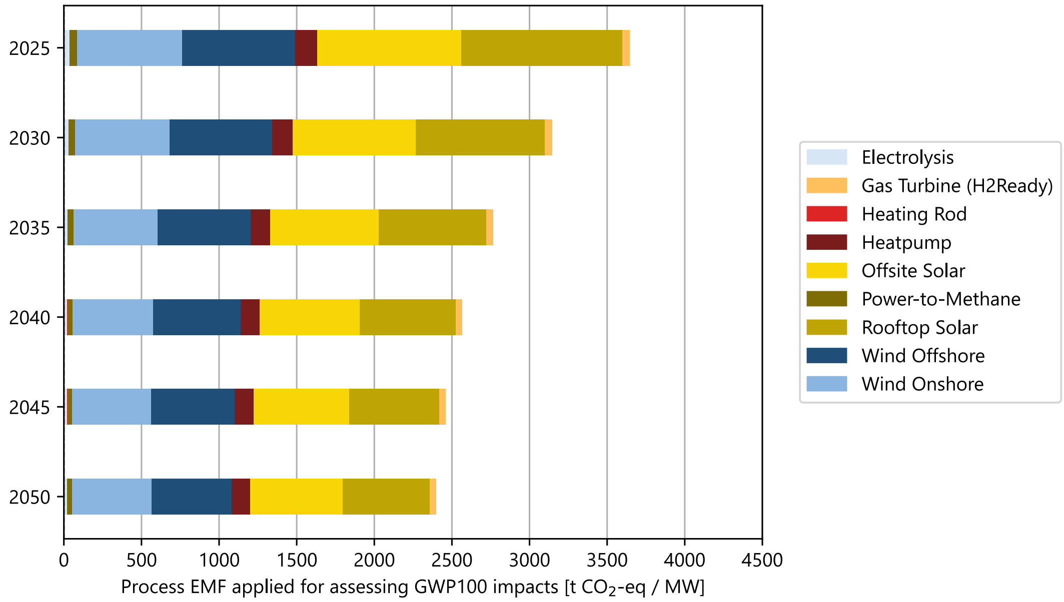
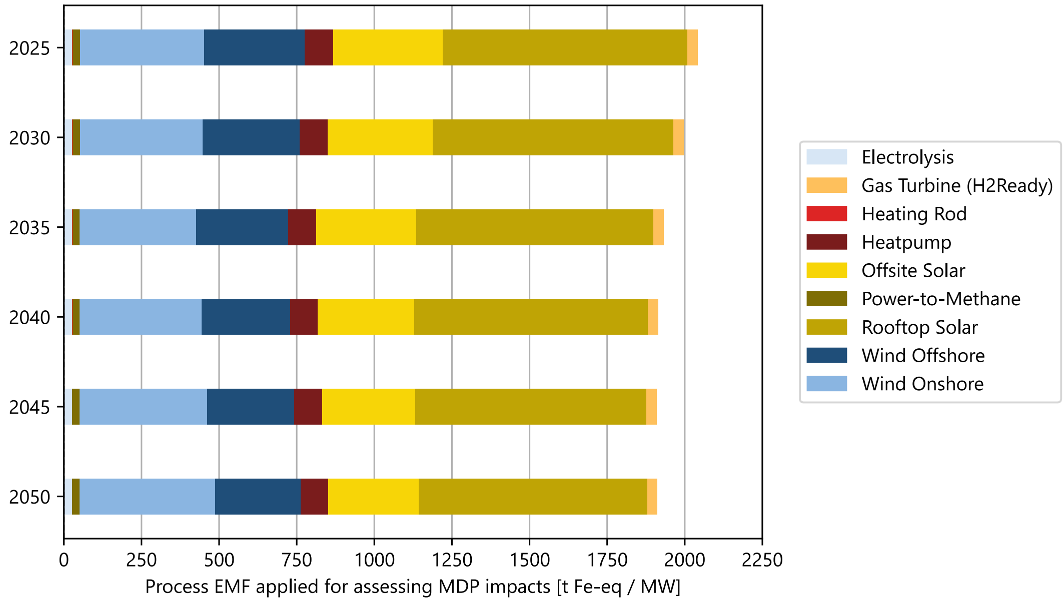
[1] Green hydrogen is a classification of hydrogen production that refers to hydrogen produced by electrolysis using electricity generated from RES.

offsite solar plants (Hengstler et al., 2021), which induce a proportionally higher need for metal resources in order to provide the same capacity amount.

For storage technologies in Figure 4.9, on the other hand, we can identify the proportionally high impacts of 1^{st} life battery manufacturing with respect to other storage options; indeed, batteries have a GWP of up to 165.7 t CO_2-eq / MWh in 2025. The repurposing of BEV batteries to 2^{nd} life stationary batteries also has non-negligible GWP impacts: its maximal GWP lies at 68.3 t CO_2-eq / MWh in 2025. Indeed, since the remanufacturing process of batteries has very low GWP impacts, the high material utilization for producing the battery and power electronics container is responsible for this relatively high EMF. On the other side, the carbon footprint associated with the ICT requirements for having a charging infrastructure capable of bidirectional charging is particularly low with a GWP of up to 5.3 t CO_2-eq / MWh in 2025. The

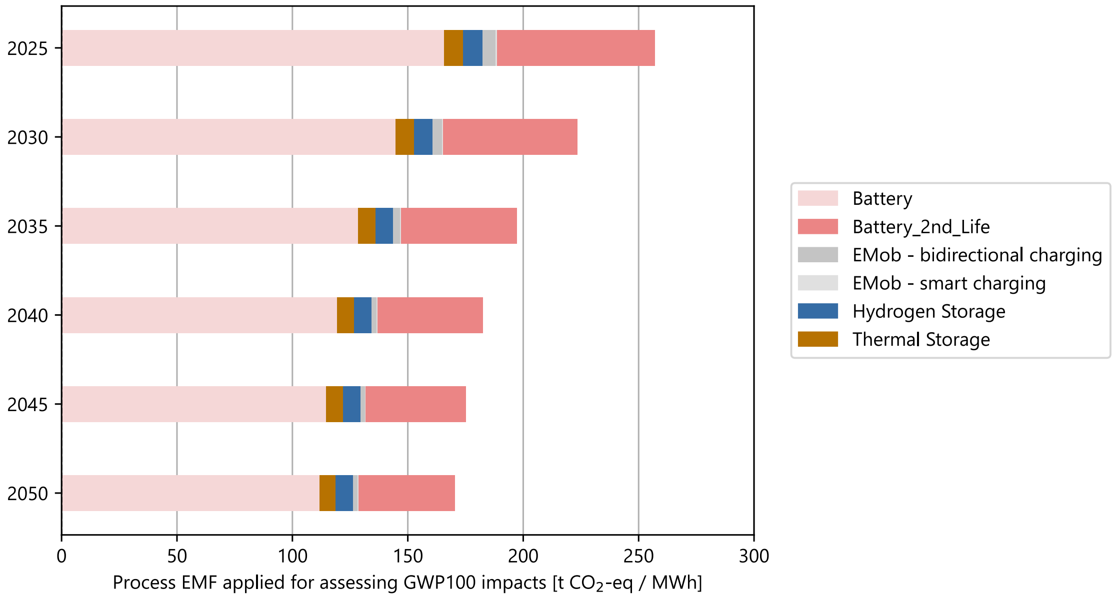


(a) GWP

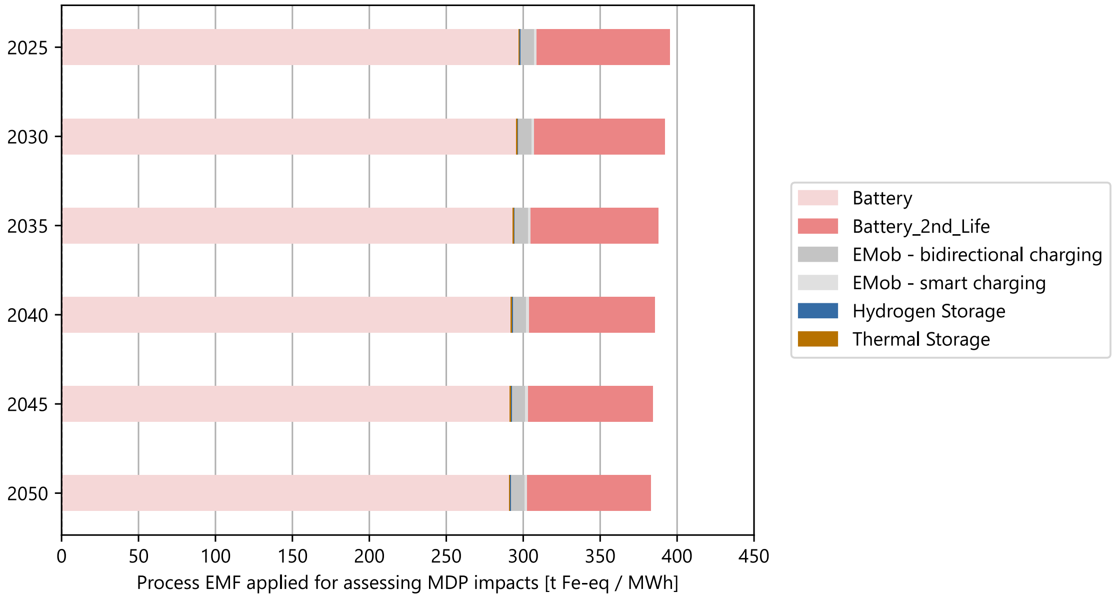


(b) MDP

Figure 4.8 EMFs for the evaluated impact categories associated with the construction of 1 MW of generation capacity. The stacking of EMFs does not have any particular meaning but serves the purpose of visualization.



(a) GWP



(b) MDP

Figure 4.9 EMFs for the evaluated impact categories associated with the construction of 1 MWh of storage capacity. The stacking of EMFs does not have any particular meaning but serves the purpose of visualization.

environmental impact of 1st life batteries becomes even more pronounced when looking at the EMFs for MDP (see Figure 4.9b) due to their particularly high need for raw and critical metal resources. These insights become particularly important in light of the weight BESS options have on the plant expansion savings and expenditures induced by the deployment of V2G and, thus, should play a major role in the overall differential pLCA impacts.

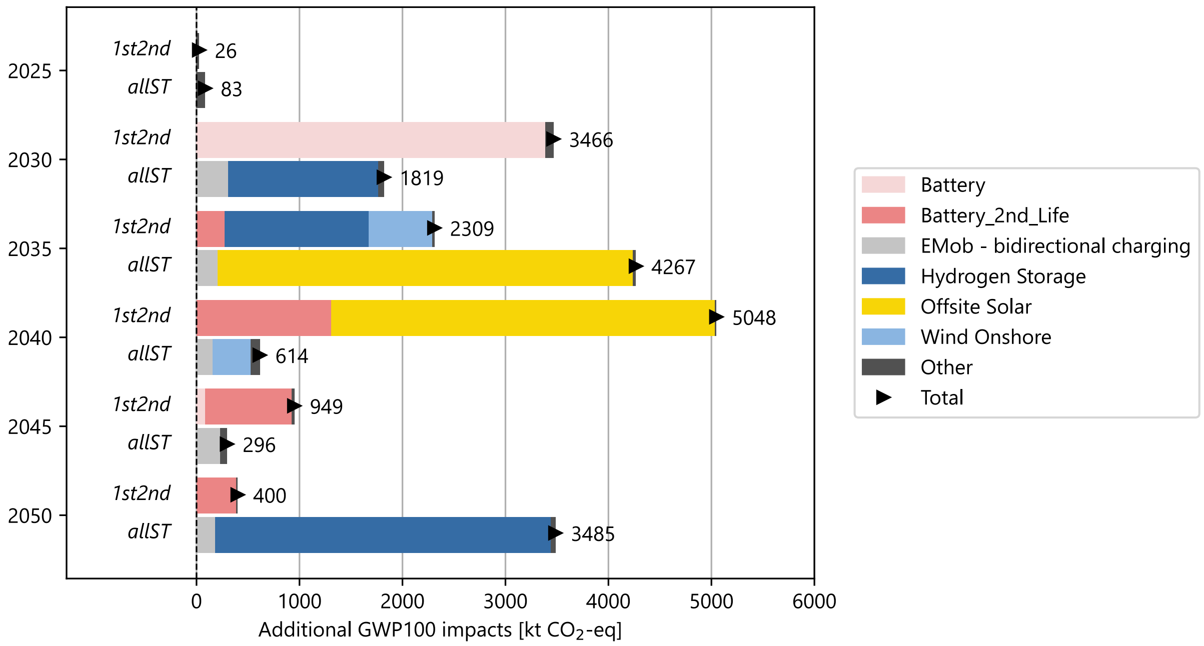
Impact scores The LCIA results, i. e. the life cycle divergences in the construction phase between both scenarios, are shown in Figure 4.10. For the sake of interpretation, we recall that all impacts associated with *1st2nd* are impacts that can be saved by deploying V2G services at a large scale, while all impacts associated with *allST* are impacts that supplementarily occur in this context. Exact values for these savings and expenditures can be found in Tables A.22 and A.23 of the Appendix, respectively. It shall be noted that, in this representation, the impacts have been broken down to the evaluated expansion year by dividing the additional construction impacts in a time step by the number of expansion years comprised within this step – i. e. by 5, in our case. Moreover, due to the characterization of process flows to the same unit, we are able to generate a single construction impact score for both generation and storage plants. As a complement, Table 4.3 provides the yearly impact difference, which can be assigned to the deployment of bidirectional charging strategies. The results have been calculated as the difference in each expansion year of the overall additional impacts in *allST* in relation to the overall additional impacts in *1st2nd*; hence, positive results indicate impact expenditures induced by the V2G measure while negative results indicate impacts which might be saved by this measure. It shall be noted that the sum only takes into account the impact difference arising in the individual expansion years and is not representative of the totality of impacts occurring over the entire investigated time frame. However, due to our assumptions on the uniformity of impacts over all years comprised in a time step, sums are still representative of potential impact saving or expenditure tendencies brought forth by bidirectional charging.

Let us first make some general statements before going into detail. According to Table 4.3, in the context of power plant capacity expansion, the deployment of V2G might enable saving approximately 1634 kt CO_2-eq of GHG emissions and 3097 kt Fe-eq of metal resources in the evaluated expansion years. Within our differential point of view, this equates to a 14% and 56% decrease in GWP impacts and MDP impacts, respectively. These results have to be further nuanced by combustion-related impact divergences, as will be done in Section 4.3.2.

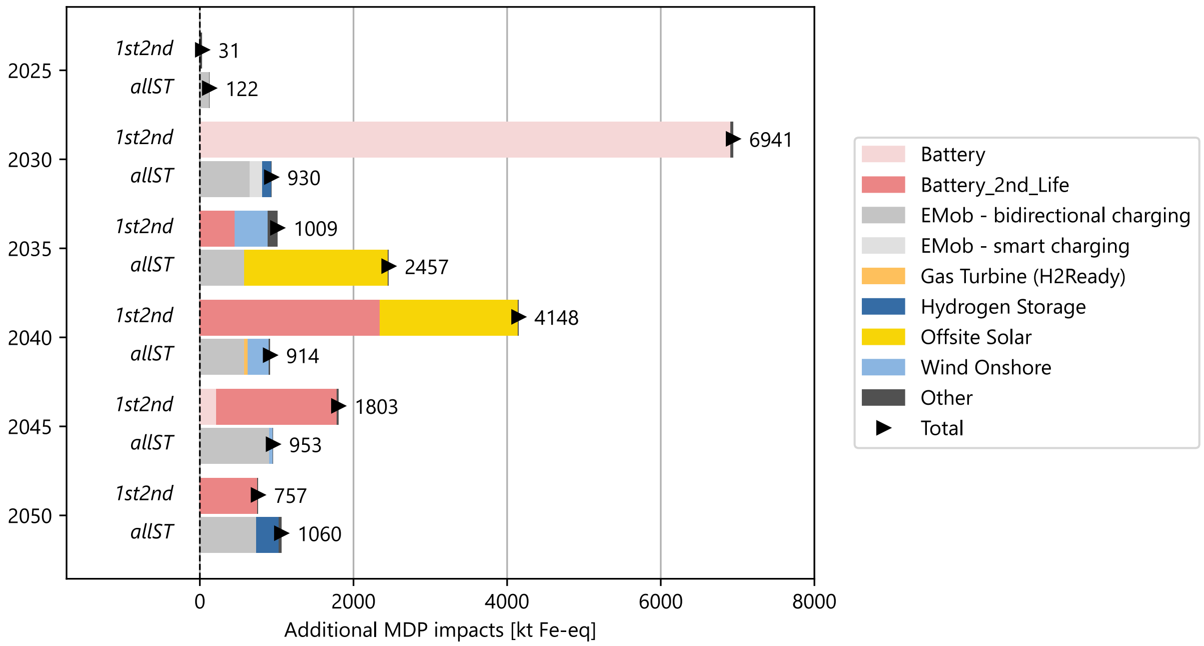
As anticipated, the scenario-based reliance on BESS flexibility options plays an essential role in the overall additional construction impacts. In case of a V2G deployment, 6316 kt CO_2-eq may be saved in the evaluated expansion years due to the avoidance of 1st and 2nd life battery manufacturing, which represents around 52% of all impact savings induced by this measure. This part is even more striking when considering MDP impacts, as batteries make up approximately 84% of the totality of metal resource savings brought forth in this context, which amounts to around 12278 kt Fe-eq in the evaluated expansion years. However, the environmental cost of upgrading BEV charging infrastructure to be capable of performing bidirectional charging should not be neglected either. Indeed, the impacts associated with bidirectional charging ICT requirements in the evaluated expansion years tally at approximately 1161 kt CO_2-eq and 3575 kt Fe-eq, which represent 11% and 56%, respectively, of the overall GWP and MDP impact expenditures induced by V2G. This value should nonetheless be mitigated by the fact that we hypothesized that each BEV capable of performing V2G uses its own charging infrastructure; hence, by sharing charging stations, environmental impacts induced by additional ICT requirements might be further reduced. In total, providing flexibility through mobile BEV storage enables saving 5155 kt CO_2-eq and 8703 kt Fe-eq in the evaluated expansion years with respect to stationary storage supply. These savings can be largely explained by the particularly high utilization of polluting raw metals for the manufacturing of battery packs and containers, which are required for the production of stationary BESS and which have considerable impacts for both GWP and MDP (see EMFs in Figure 4.9).

Next to BESS-related impacts, we can observe in Figure 4.10 that additional offsite PV capacity construction plays a fundamental role in the impacts savings and expenditures induced by bidirectional charging strategies, which is in accordance with their equally large part within the generation capacity investments of Figure 4.5. While these impacts make out a large portion of the overall impact balance, they are, for the most part, compensated between both scenarios. Indeed, looking specifically at GWP impacts (Figure 4.10a), in *allST* around 4036 kt CO_2-eq of additional impact expenditures stem from offsite PV in 2035, while in *1st2nd* this technology brings forth around 3724 kt CO_2-eq of impact savings in 2040; thus, in total, in the evaluated expansion years, impacts originating from the construction of offsite solar panels only emit 312 kt CO_2-eq extra in the case of V2G deployment, which is negligible on a large scale. This can be explained by the time shift in the construction of PV capacity from the moment RE expansion becomes an endogenous ISAaR parameter in 2035, as discussed in Section 4.2.1. The same holds true for the MDP impacts of offsite PV.

As a last noteworthy additional construction impact, we can mention GWP impacts associated with hydrogen storage (see Figure 4.10a). Indeed, in 2050, an additional 3261 kt CO_2-eq are supplementarily



(a) GWP



(b) MDP

Figure 4.10 Environmental impacts associated with the additionally constructed capacity in the *1st2nd* and *allST* scenarios with respect to the other scenario

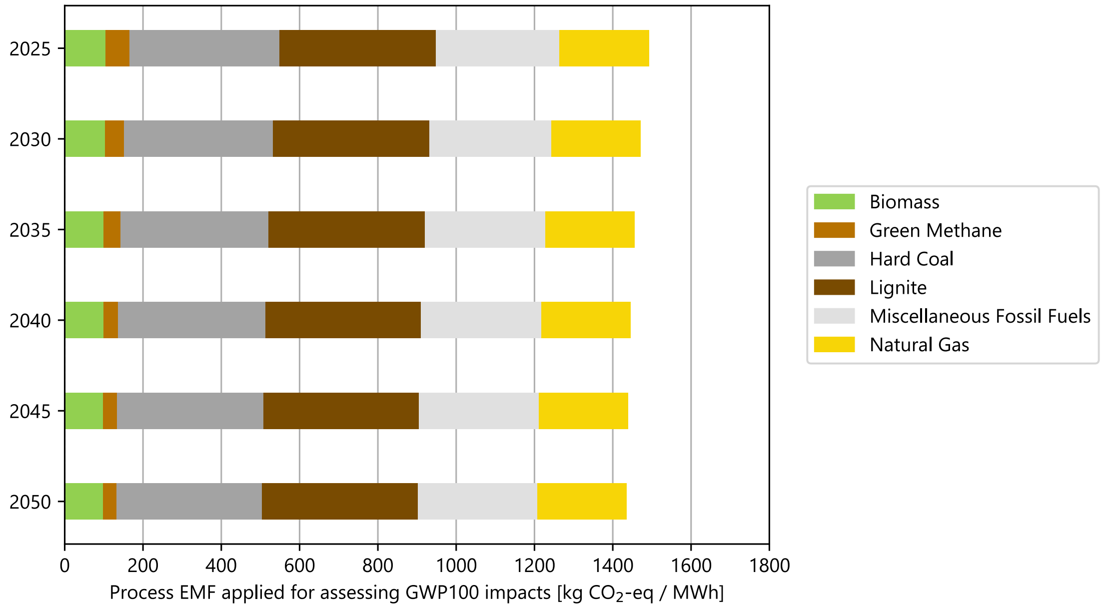
	2025	2030	2035	2040	2045	2050	**Sum**
GWP [kt CO_2-eq]	+57	-1647	+1958	-4434	-653	+3085	**-1634**
MDP [kt Fe-eq]	+91	-6011	+1448	-3234	-850	+303	**-8253**

Table 4.3 Impact difference induced by the deployment of V2G strategies during capacity construction. Positive values indicate additional impacts induced by this measure, while negative values indicate impact savings.

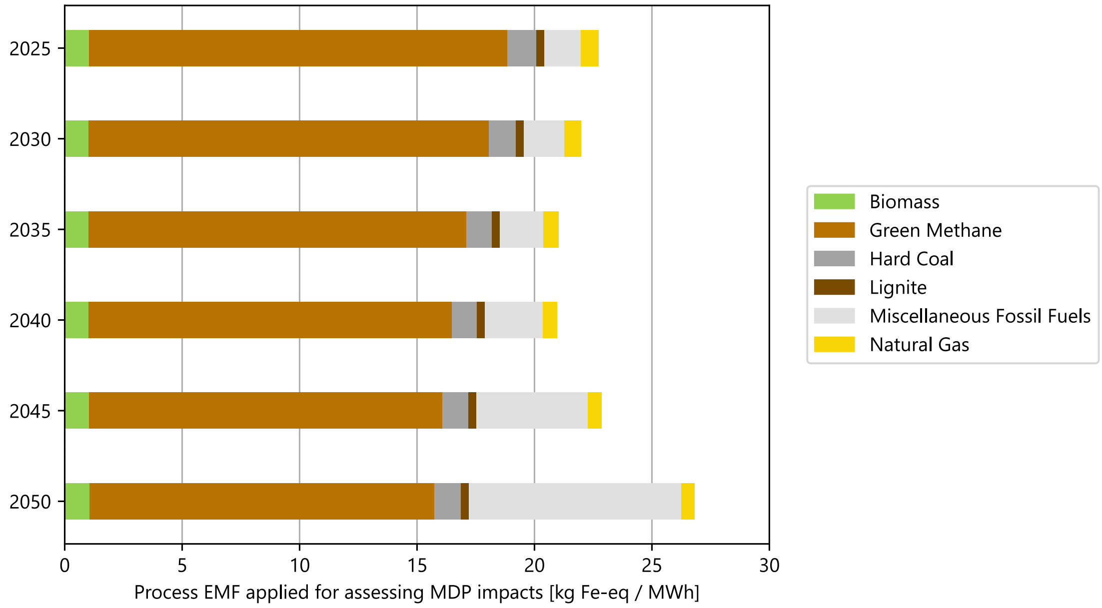
emitted in the case of V2G deployment on account of this technology without being compensated in any expansion year. These emissions arise proportionally to the additional expansion of hydrogen storage capacity in 2050 in *allST* visible in Figure 4.5. Nonetheless, it shall be recalled that the EMF of this technology might not be representative of actual impacts due to the lack of information in this regard (see discussion in Section 4.2.1).

4.3.2 Use Phase

Emission factors We now consider the use phase of the energy supply sector, for which we proceed analogously to its construction phase. In line with the LCIA methodology in Section 3.2.3, we analyze the



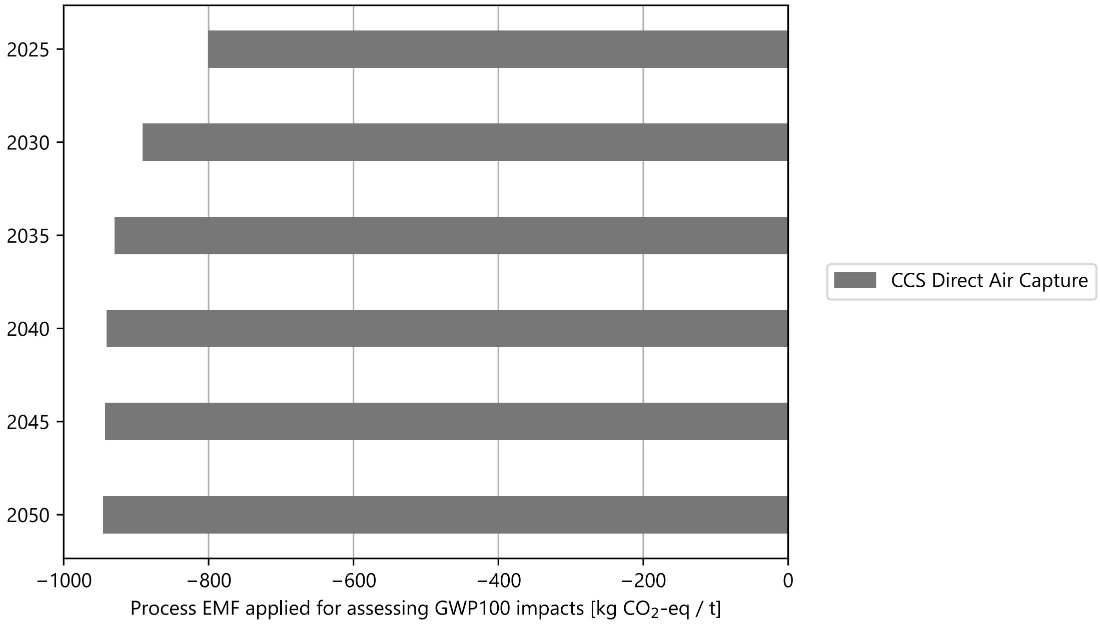
(a) GWP



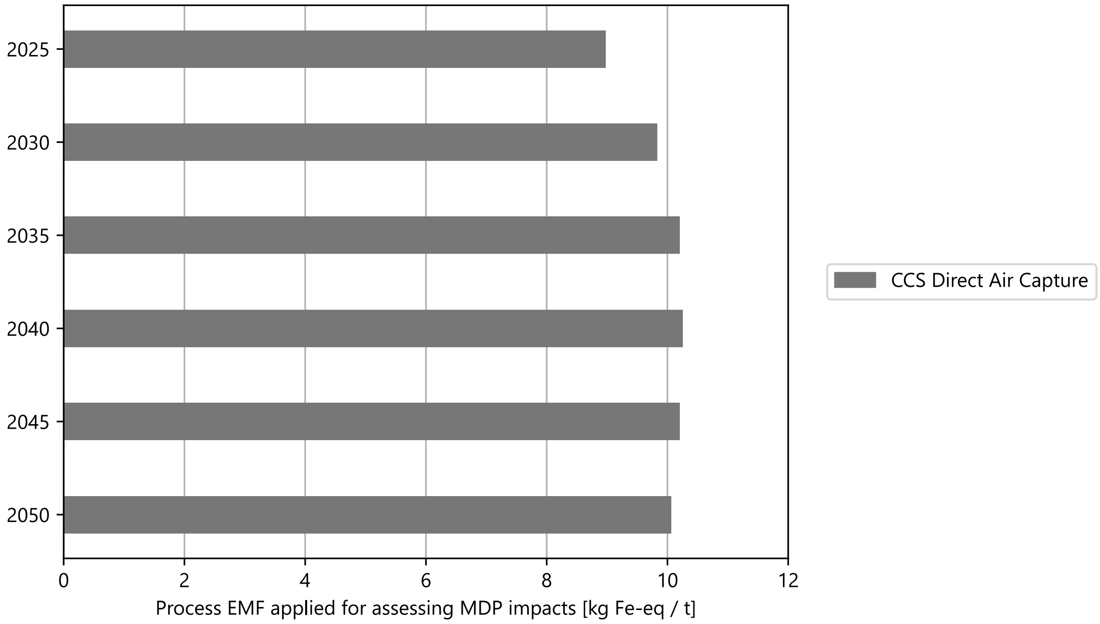
(b) MDP

Figure 4.11 EMFs for the evaluated impact categories associated with the supply of 1 MWh of primary energy carrier. The stacking of EMFs does not have any particular meaning but serves the purpose of visualization.

EMFs associated with the import and, in the case of fossil fuels, combustion of primary energy carriers. Figure 4.11 portray the EMFs for 1 MWh of imported/burned energy. In line with our expectations, the combustion of fossil energy carriers is associated with a particularly high EMF for GWP (see Figure 4.11a), with hard coal and lignite reaching an EMF of around 400 kg CO_2-eq / MWh. Despite the fact that natural gas combustion is less polluting than that of other fossil fuels, its GWP in 2025 still more than half as high as lignite or hard coal combustion. We can also note that even though the use phase-related EMFs for GWP tend to decrease over the expansion years, their rate of decline is very low. We can explain this by the fact that direct GHG emissions caused by burning fossil resources have little playroom for reduction. Unlike their GWP, fossil fuel combustion has proportionally low impacts on MDP (see Figure 4.11b). In



(a) GWP



(b) MDP

Figure 4.12 EMFs for the evaluated impact categories associated with the capture of 1 t of CO_2. The stacking of EMFs does not have any particular meaning but serves the purpose of visualization.

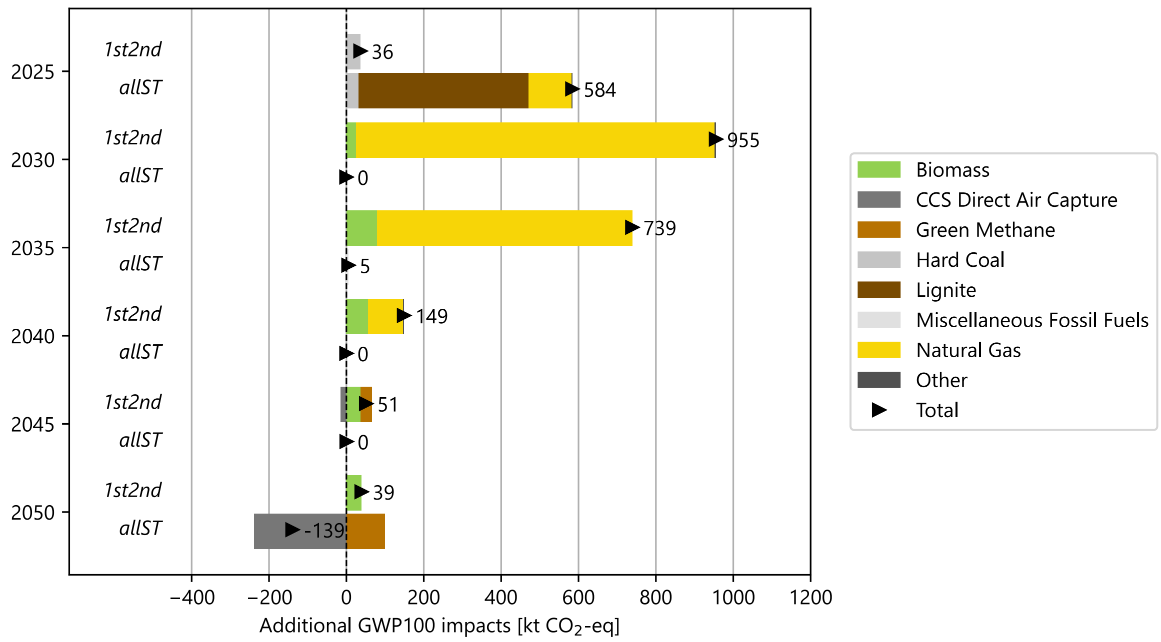
contrast, green methane import has the highest EMF in this impact category; we might explain this by the metal consumption required for the manufacture of electrolysis and methanation conversion plants in countries supplying these imports. It is further noteworthy that the MDP impacts associated with the combustion of 1 MWh of diesel are the only ones that do not decrease in future years but, on the contrary, increase. We hereby hypothesize that this is due to upcoming supply difficulties caused by the scarcity and depletion of this resource, calling for increasingly complicated extraction techniques.

Lastly, the energy system's use phase is further characterized by the capture of CO_2 emissions through CCS. Figure 4.12 portrays the GWP and MDP impacts associated with the capture of 1 t of CO_2. Coherently the EMF for GWP for this technique is negative, since CO_2 is removed from the atmosphere. However, due to the upstream and downstream processes required by the application of CCS (e. g. the construction of a CCS facility or the electricity consumption needed for compressing the CO_2), the direct air capture of 1 t of CO_2, does not equate to a GWP reduction of 1 t CO_2-eq but of at most 0.95 t CO_2-eq in 2050. Furthermore, while GWP impacts of CCS are negative, its MDP impacts are positive since the process necessitates metal resources for its operation.

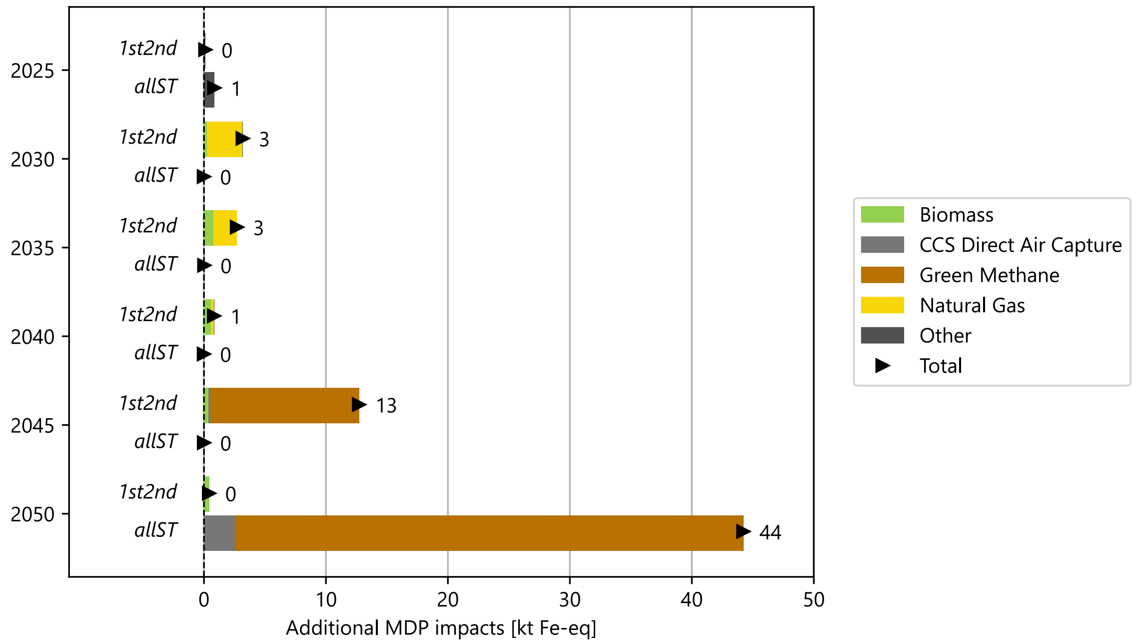
Impact scores The life cycle impact scores of the use phase resulting from the framework's LCIA characterization can be seen in Figure 4.13; exact values can be consulted in Tables A.24 and A.25 of the Appendix. Energy combustion and CO_2 capture impacts have been merged to a single impact score within the scope of our assessment thanks to the characterization of the LCI to an identical impact indicator unit. Again, any impacts saved by deploying V2G services are attributed to the *1st2nd* scenario, and all impacts additionally arising in this context are consolidated within the *allST* scenario results. Table 4.4 further provides the difference in GWP and MDP impacts arising in the evaluated expansion years during the use phase; we recall that positive results indicate additional expenditures and negative results potential savings brought forth by a bidirectional charging policy. The sum mirrors impact balance tendencies.

In general terms, we can note that 1519 kt CO_2-eq can be saved through the deployment of V2G strategies in the evaluated expansion years, which, within the scope of our differential viewpoint, amounts to a reduction of the additional GWP of 77% with respect to a scenario where no bidirectional charging is implemented. These savings are of same order of magnitude than savings induced by the construction phase. Looking specifically at the impact distribution among energy carriers in Figure 4.13, we can see that the savings stemming from the large-scale deployment of V2G are, for the most part, due to the ancillary natural gas combustion and biomass imports in *1st2nd* identified in Figure 4.7a. Likewise, we can note that the majority of additional GWP impacts arising in a bidirectional charging context are induced by increased lignite combustion in *allST* in 2025. Moreover, in a bidirectional charging setting, a considerable amount of emissions can be saved by an ancillary recourse to CCS – these savings amount to -223 kt CO_2-eq in all expansion years comprised in our pLCA. We can further see that despite the high additional investment in green methane in the case of V2G deployment (63% of the additional investments in *allST*), this energy carrier does not significantly contribute to the overall additional impacts arising in this context (only 22% of the additional emissions in *allST*).

Now, looking at MDP impacts of the deployment of bidirectional charging strategies in Figure 4.13b, 45 kt Fe-eq of metal resources are additionally depleted in this context in the evaluated expansion years, most of which can be attributed to the supplementary import of green methane. Indeed, green methane represents about 93% of the ancillary metal resource utilization in a V2G context, which is in line with the particularly high EMF associated with the import of this energy carrier identified in Figure 4.11b. On the contrary, the MDP impact of the additional combustion of fossil resources in a scenario where no V2G services are deployed is very low. Thus, on the whole, the use phase MDP impact distribution is not representative of the actual resource disparities observed in Figure 4.7 but rather reflects the EMF divergences of the ISAaR technologies associated with this life phase. Despite all this, the MDP impact expenditure and saving values are very low on an absolute scale and do not represent considerable environmental consequences.



(a) GWP



(b) MDP

Figure 4.13 Environmental impacts associated with the additional energy carrier transactions allocated to the energy supply sector in the *1st2nd* and *allST* scenarios with respect to the other scenario

	2025	2030	2035	2040	2045	2050	**Sum**
GWP [kt CO_2-eq]	+548	-955	-734	-149	-51	-178	**-1519**
MDP [kt Fe-eq]	+1	-3	-3	+1	-13	+44	**+27**

Table 4.4 Impact difference induced by the deployment of V2G strategies during the facilities' use phase. Positive values indicate additional impacts induced by this measure, while negative values indicate impact savings.

4.4 Interpretation

Following the LCIA of both the energy system's construction and use phase by the automated framework, the interpretation is left to the discretion of the user. Indeed, this is the only pLCA step for which we do not obtain direct results from the framework and for which no methodology has been set up in Chapter 3. Thus, in order to tackle this step, we will, as a first step, consolidate the individual results of each life phase to be able to draw general conclusions on the environmental impacts of the deployment of V2G strategies from an energy system's perspective. With this, we will reflect on the research questions defined in Section 1.3. We will then round off this section with a sensitivity analysis of the results.

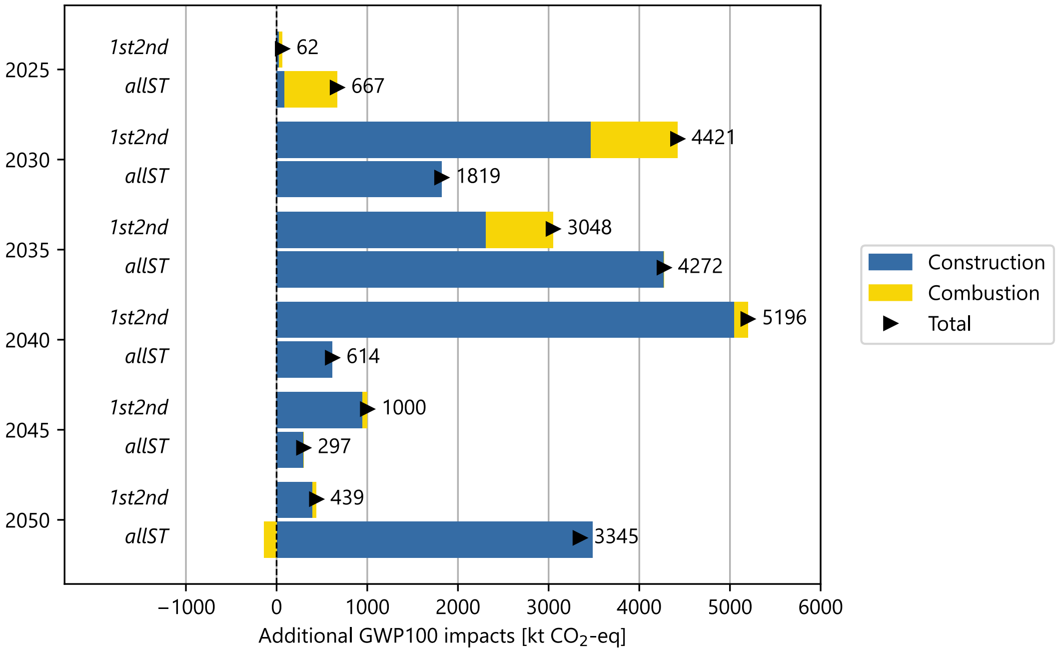
4.4.1 Consolidation of Both Life Phases

Having computed the additional energy system construction and use phase life cycle impacts of each scenario, we can consolidate individual life phase scores to obtain a single score across both life phases. This amounts to adding the results of Figures 4.10 and 4.13, which has been done in Figure 4.14; it should, thus, be interpreted in the same way. To complement this representation, Figure 4.15 portrays the weight each life phase has on the additional impacts induced by V2G technology deployment (*allST* scenario) or saved by such a measure (*1st2nd* scenario) in each expansion year. Likewise to the individual life phase results, Table 4.5 further provides values for the overall impact difference that can be assigned to the deployment of V2G strategies.

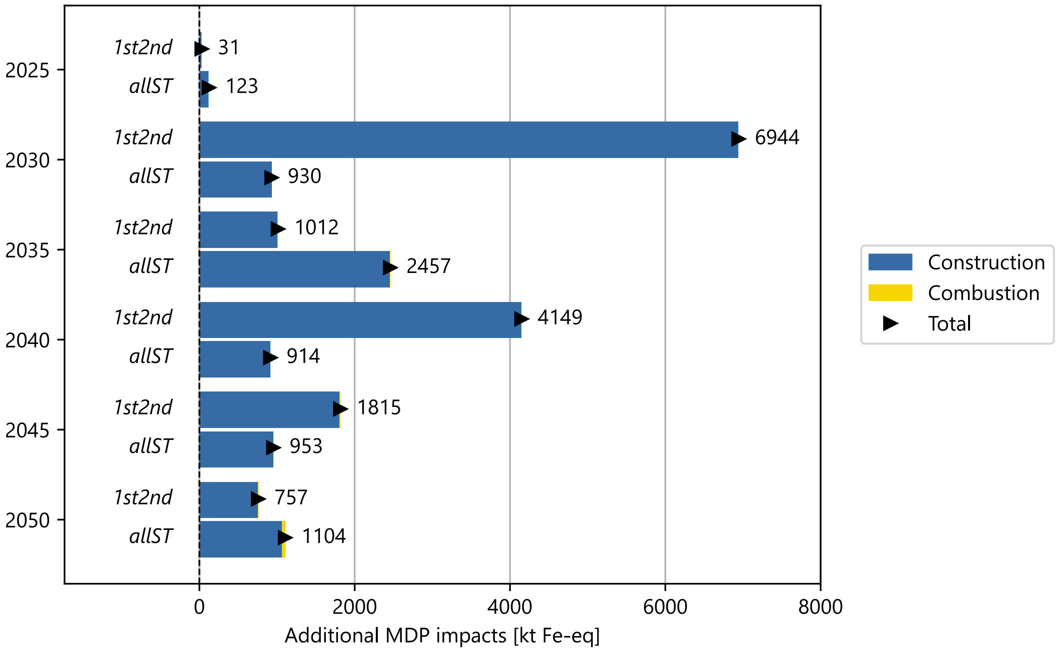
In the evaluated expansion years, the deployment of V2G strategies in *allST* enables saving 3136 kt CO_2-eq and 8227 kt Fe-eq on the energy system's life cycle impacts. Thereby, the use phase makes out a relatively small part of the additional GWP impacts induced by this measure (4%), while its part is non-negligible within the GWP impacts saved thanks to this measure (14%). Looking at Figure 4.15a and comparing it with Figure 4.5, the large part of the use phase in the GWP savings and expenditures in 2025 stems from the particularly low amount of capacity taken into operation in that year for both scenarios. Regarding the MDP impact category (Figure 4.15b), nearly all of the savings and expenditures associated with V2G deployment arise during the construction phase. This is due to the particularly low absolute MDP impact difference in the energy system's use phase, which is to be expected since BESS – constituting the major divergence in both scenarios – do not require primary energy carrier input in their use phase.

From Table 4.5, it can further be inferred that the absolute difference in the prospective energy system impacts induced by bidirectional charging varies very strongly according to the expansion year. Following the discussion on the life phase contributions to the overall results held just above, this is especially due to the fluctuations of the difference in capacity construction between both scenarios (see Table 4.3). Hence, no particular temporal pattern can be established concerning the impact difference of the deployment of V2G as, in some expansion years, this measure induces a – within the scope of our differential point of view – high amount of additional impacts, while in other years, a high amount of impacts can be saved through this measure. Taking GWP as an impact category, a tendency toward a saving of GHG emissions thanks to the deployment of bidirectional charging strategies can be identified due to the avoidance of stationary BESS manufacturing (see discussion in Section 4.3.1). For MDP, this tendency is amplified.

Figure 4.16 illustrates the cumulative additional impacts of each scenario over the entire assessment time frame – and not only in the expansion years. This representation has been realized based on our assumption that the additional investments of the energy system do not vary over a time step. Thus, the curve of cumulative additional impacts is piecewise linear, and its slope varies every five years. The area between the two curves outlines the total environmental impact savings and expenditures induced by the deployment of bidirectional charging up to the considered year. In years where the curve associated with *allST* is above the one associated with *1st2nd*, we are in an expenditure situation; in the event of the opposite, we are in a saving situation. It is interesting to note that for the GWP impact category (Figure 4.16a), we are in a saving situation starting from 2027, and for the MDP impact category (Figure 4.16b) starting from 2026. This is especially surprising in light of the high fluctuations observed between expansion years. All in one, the deployment of V2G strategies enables saving approximately 14.9 Mt CO_2-eq and



(a) GWP

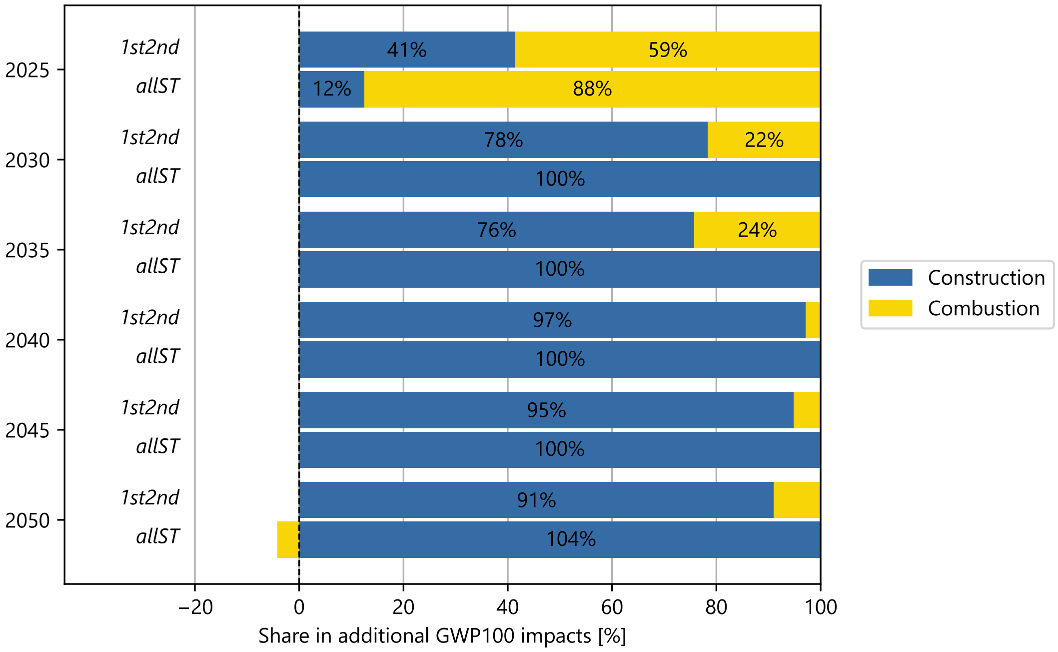


(b) MDP

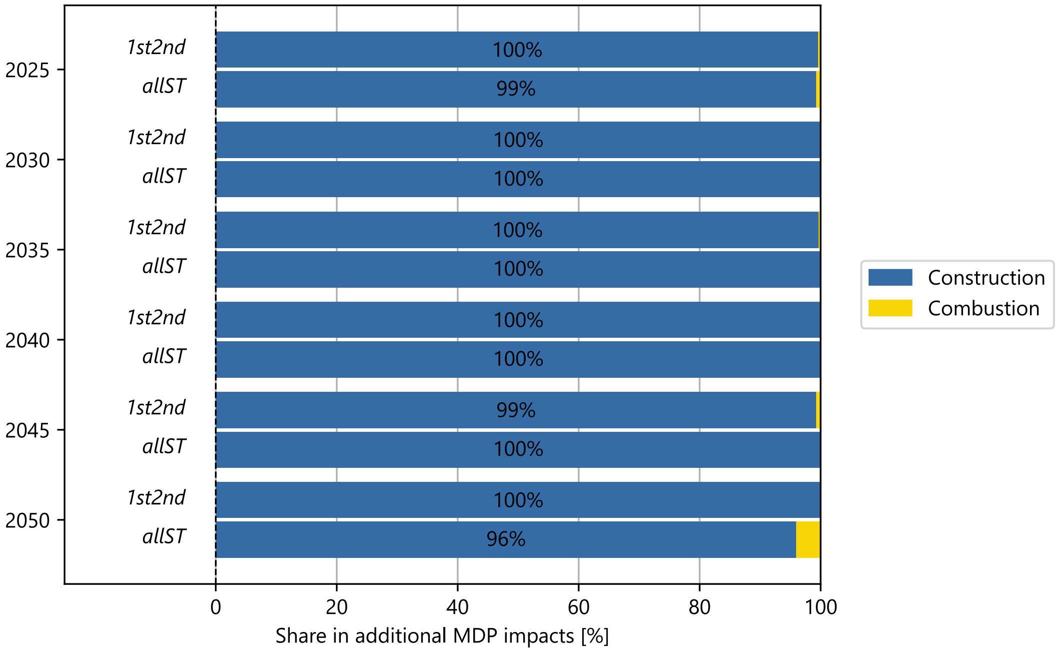
Figure 4.14 Additional environmental impacts across all evaluated energy system life phases in the *1st2nd* and *allST* scenarios with respect to the other scenario

	2025	2030	2035	2040	2045	2050	**Sum**
GWP [kt CO_2-eq]	+596	-2602	+1224	-4582	-703	+2906	**-3136**
MDP [kt Fe-eq]	+92	-6014	+1445	-3235	-862	+347	**-8227**

Table 4.5 Impact difference induced by the deployment of V2G strategies across all evaluated facility life phases. Positive values indicate additional impacts induced by this measure, while negative values indicate impact savings.



(a) GWP

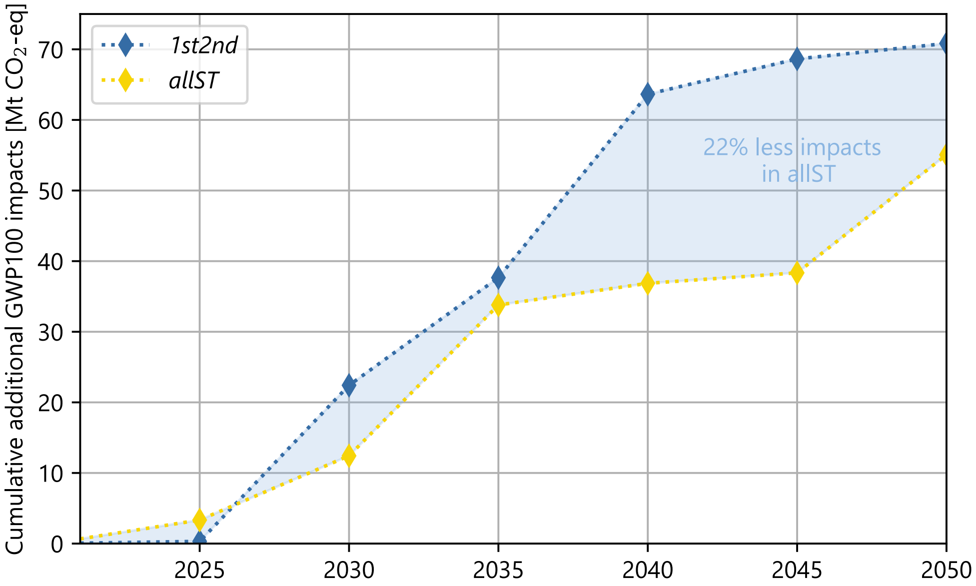


(b) MDP

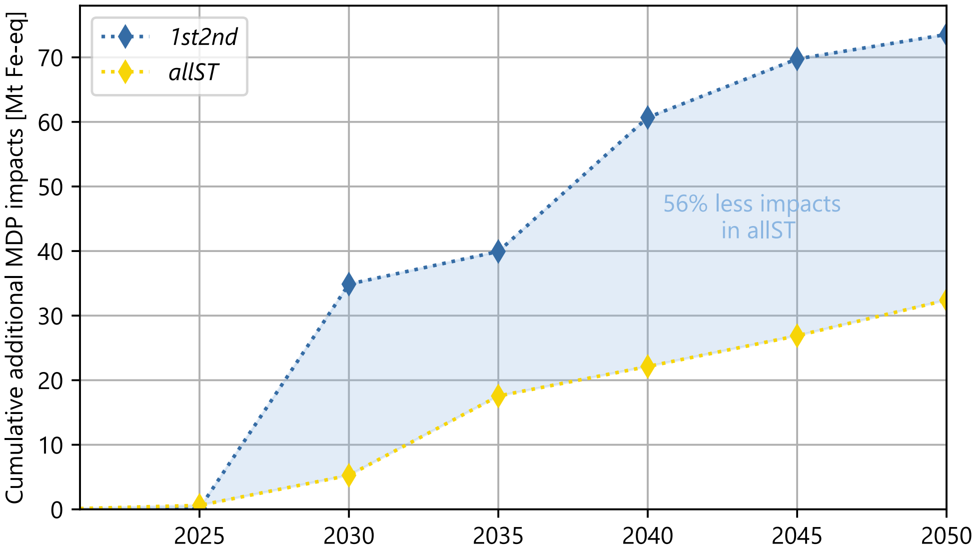
Figure 4.15 Life phase share in the additional impacts of the energy system in the *1st2nd* and *allST* scenarios with respect to the other scenario

41.1 Mt Fe-eq on the projected energy system expansion, which, within our differential point of view, represents a 22% reduction of the energy system's GHG emissions and a 56% reduction of its metal resource utilization.

It should be noted that these results are particularly sensitive to ISAaR, ecoinvent, and *premise* modeling and parameter conjectures. Thus, ISAaR and IAM projections are not representative of actual future states but are strongly biased based on their input parameters, assumptions, model structure, and optimization methodology; slight model modifications might induce considerable divergences in our pLCA results. As to the ecoinvent DB, process flow inventories and characterization factors are subject to uncertainty, which



(a) GWP



(b) MDP

Figure 4.16 Cumulative overall additional energy system impacts in the *1st2nd* and *allST* scenarios with respect to the other scenario

has been neglected within the framework of the thesis. Moreover, the chosen generic LCI background processes are not necessarily representative of the characteristics of individual ISAaR technologies and might create some additional bias in our results. In reality, impacts will differ for each distinct power plant, be it, among others, because of its industrial construction process, supplied material provenance, or site location.

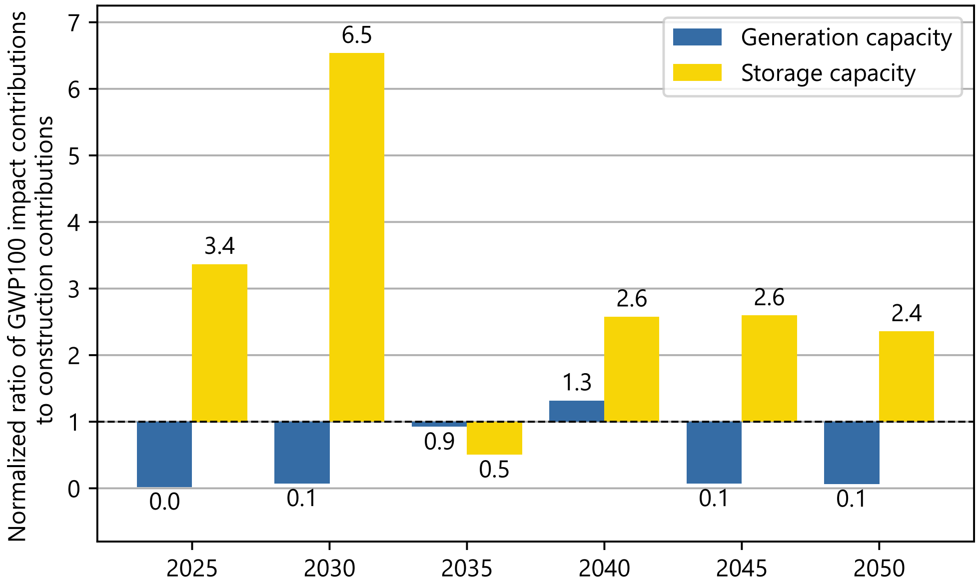
We have seen that GWP and MDP impact savings particularly arise from the avoided manufacture of stationary batteries due to their high demand for critical raw metals for producing battery packs and containers. However, this inference should be mitigated by the necessary battery manufacturing for BEVs, which is out of the scope of the pLCA. Indeed, to be able to provide sufficient V2G storage potential, enough BEVs must be in circulation and connected to charging infrastructure simultaneously. In the ISAaR scenarios modeling, it has been hypothesized that the deployment of bidirectional charging strategies does not have any influence on the number of BEVs available for storage; hence, no battery manufacturing impacts have been associated with the provision of storage through V2G. However, going beyond the scope of the model, it could be that solely relying on this technology in the future might induce a higher production of BEVs and, by extension, 1st life battery packs, as well as supplemental load in the system. On top of that, we have not accounted for the enhanced BEV battery pack aging induced by the increased charging cycles brought forth by bidirectional charging. Hence, V2G might speed up the need to replace BEV batteries or even the entire car, again inducing ancillary environmental impacts. At this point, it is interesting to note that our results stand in opposition with the findings of Zhao and Baker (2022), which assess that the prospective GWP and MDP of delivering 1 kWh of electricity is higher when using mobile BEV storage for flexibility provision than when employing stationary batteries. Indeed, unlike our work, this study considers environmental impacts arising from BEV battery manufacture and aging in their LCA. Moreover, the deployment of bidirectional charging strategies supposes that incentives toward BEV and bidirectional charging infrastructure ownership are established by the government. Thus impact savings elaborated within our pLCA should be confronted with the environmental impact reduction potential brought forth by limiting car purchases and travel and promoting sobriety. On the other hand, we should also note that when V2G strategies are not deployed, the ISAaR model heavily relies on stationary 2nd life batteries for providing flexibility. Yet, as these batteries are manufactured using old BEV batteries, the same considerations as before play a role in the potential advantages of promoting stationary BESS. On top of that, the additional life cycle impacts induced by the V2G measure within the scope of our pLCA might be reduced by sharing charging infrastructures between households or financing public charging stations capable of performing bidirectional charging.

For all the reasons stated above, the pLCA impacts savings achieved by deploying V2G strategies are not representative of a clear advantage of BEV-based storage provision from an energy system's point of view. Furthermore, it shall be noted that the difference in the energy system's GWP impacts is relatively low compared to the current combustion-related GHG emissions of the energy supply sector in Germany, which the German Environment Agency estimates at about 240 Mt CO_2-eq in 2021 (Umweltbundesamt, 2023a). This annual value, which does not even take into account any life cycle considerations, already represents over 15 times the amount of prospective GHG emission savings yielded by our pLCA over the whole time frame. As another way of looking at the pLCA GWP results, V2G deployment would enable saving the CO_2-eq emissions per capita of about 48 000 current German citizens or 90 000 German citizens in 2050 each year over the studied time frame (Umweltbundesamt, 2023b). Hence, from a big-picture perspective, the saved GHG emissions elaborated within our pLCA are marginal when it comes to creating a noticeable ecological impact. Regarding MDP impacts, Xu et al. (2021) find that for decarbonizing the European energy system by 2050, total life cycle system expenditures require 470 to 2200 Mt Fe-eq of metal resources. Thus, our elaborated savings for Germany represent 1.9 to 8.7% of that range. Considering the difference in regional scale between both results, we deem this part in potential savings to be meaningful enough to conclude that deploying V2G services on a large scale would enable reducing metal utilization within the limitations of our work. To wrap up this discussion, the chosen impact category has a considerable influence on the ecological advantages or disadvantages that the deployment of bidirectional charging strategies might confer from an energy system's perspective; therefore, studying further impact categories in future studies might lead to new insights.

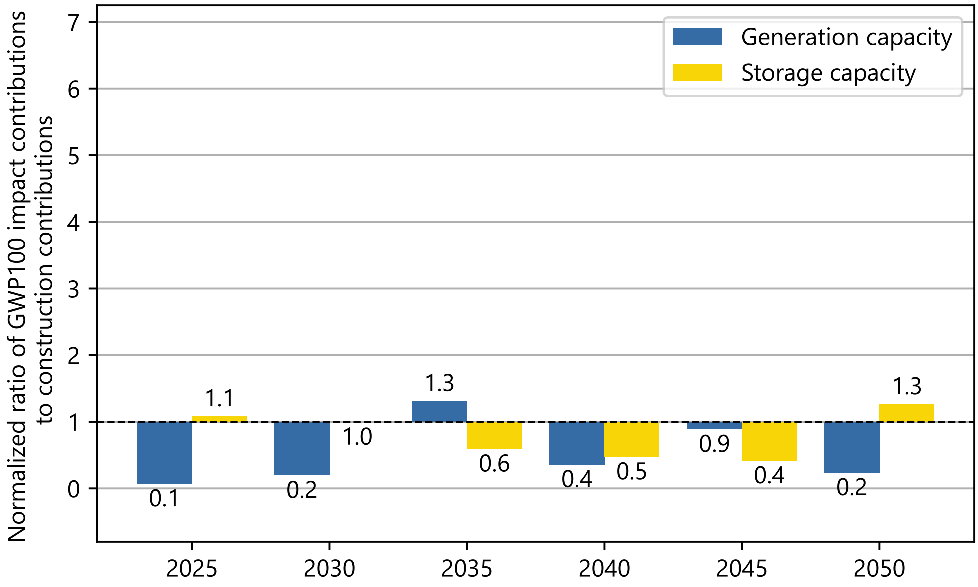
4.4.2 Sensitivity Analysis

In the following discussion, we focus on the impact category "GWP". We have seen that the GWP expenses and savings induced by the flexibility option "bidirectional charging" are very fluctuating and, thus, are very sensitive to assumptions and ISAaR optimization results. A crucial point thereby is the weight of the use phase in the overall balance. Indeed, the impact savings induced by less than a hundredth of the energy supply sector's demand for energy carriers and CO_2 capture are almost identical to the impacts savings caused by V2G strategies in the construction phase; yet we have seen that the construction phase accounts for the majority of additional impacts in both scenarios. However, even in the construction phase, some of our hypotheses have a considerable influence on the final result: we already mentioned the assumptions on the additional requirements for bidirectional charging. On the other hand, we have seen that 1st and 2nd life batteries have a considerable influence on the results due to their proportionally high EMF and their importance in the computed scenario construction difference. 1st life batteries have an even higher weight in the overall balance because of the ancillary manufacture of battery packs. In the upcoming sensitivity analysis, we will inspect these battery packs further.

Let us first analyze the relative contributions of 1st life battery manufacture with respect to the overall impacts. We have seen that GWP results vary considerably according to the additional capacity construction in each expansion year; in other words, impact peaks are correlated with construction peaks. We portray this correlation in Figure 4.17 by computing a normalized ratio between the contributions to construction and the contributions to construction impacts. By contributions, we understand the ratio between the annual investment with respect to the total investments over all years, i. e., in the case of the contributions to construction, this would be the amount of capacity constructed in an expansion year divided by the sum



(a) *1st2nd*



(b) *allST*

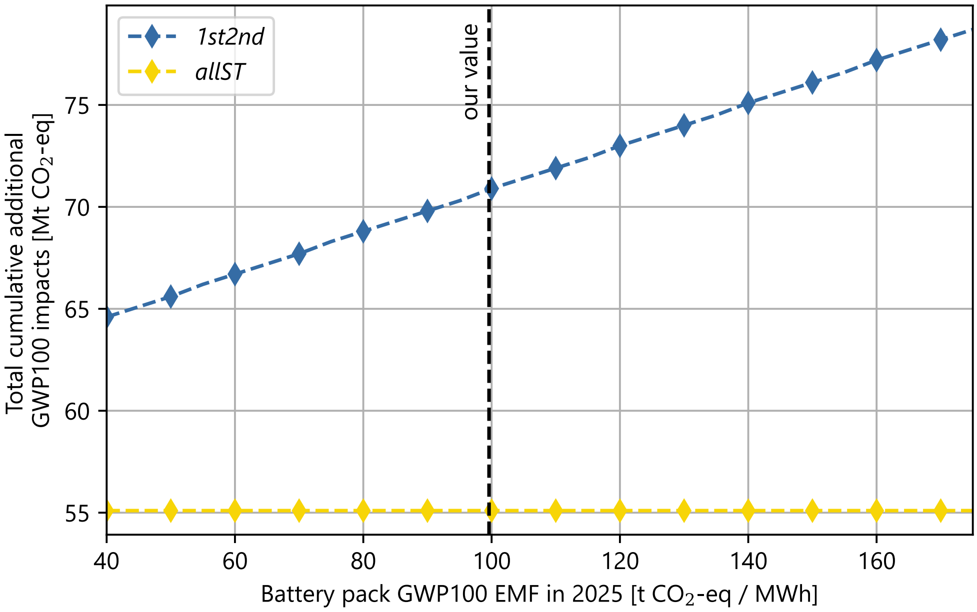
Figure 4.17 Correlation between the construction of additional capacity and the additional GWP impacts attributed to the construction phase of capacity amounts constructed over all years. Thereby, we differentiate generation and storage capacity. For the sake of example, if, in 2025, 200 GWh of storage capacity is additionally constructed in one scenario, and over all expansion years, the additional storage capacity construction of this scenario amounts to 1000 GWh, then the normalized contributions to construction in that year are 0.2. The contributions to the construction impacts are calculated analogously; we likewise distinguish between impacts attributed to the construction of generation capacity and the construction of storage capacity. Those normalized contribution values are then further put into relation by dividing the contributions to construction impacts by their corresponding contribution to construction; this renders the normalized ratio value shown in the figure. It can be interpreted in the following way: should the ratio be lower than one, then the contributions to construction are higher than the contributions to construction impacts and vice-versa. Returning to our previous example, if in 2025, the contributions to construction are still 0.2, but the contributions to construction impacts are 0.4, then the ratio is 2, and the constructed capacity plays a larger role in the additional GHG emissions of the scenario than in the provision of storage. The downside of this analysis is that it does not account for the characteristics of individual technologies featured in the additional construction.

It then becomes apparent that, in *1st2nd*, this ratio is particularly high in 2030 when looking at storage capacity: the contributions to storage capacity impacts are 6.4 fold higher than the contributions to storage capacity construction. Yet, looking at Figure 4.5, we can see that, in 2030, the additionally constructed storage capacity mainly stems from 1st life batteries. From this, we can infer that the EMF associated with this technology, as specified in Section 4.3.1, has a significant influence on the results and overall scenario differences. To examine this influence further, we conduct a sensibility analysis on the EMF value.

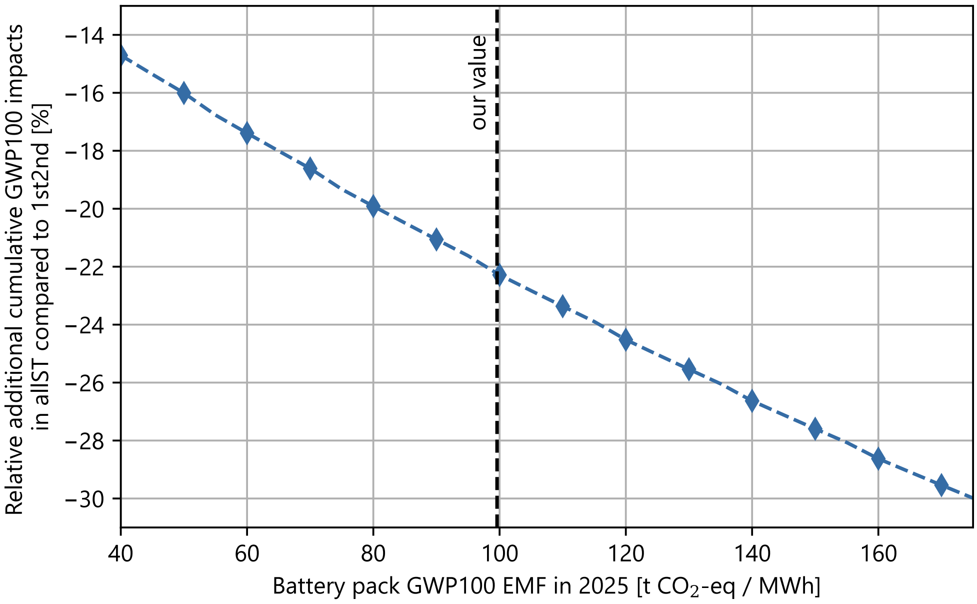
Yet, before that, we would like to share some extra insights on this figure. Proceeding as before, we can identify three other plant technologies that have above-average impacts in the context of our pLCA: 2nd life batteries, offsite PV, and hydrogen storage. Concerning 2nd life batteries, this was to be expected in light of their high need for polluting metal resources for the fabrication of the battery and power electronics container. For offsite PV, this is due to the fact that silicon-based panels are predominantly used and come with relatively high production GHG emissions (Hengstler et al., 2021; Wirth, 2023). For hydrogen storage, we cannot conclude on the accuracy of this observation due to the lack of LCI data on the construction of such plants (see discussion in Section 4.2.1). Lastly, we can highlight that the majority of ratio values for generation capacities – and for storage capacities in *allST* – are lower than one, which can be attributed to the underlying methodology for the computation of this ratio: the high impact contributions of the aforementioned facility types in the overall balance proportionally decrease all other technologies' impact contributions thus lowering their resulting ratio.

Let us now conduct the sensitivity analysis on the selected battery pack EMF for GWP. The ecoinvent process based on Dai et al. (2019) selected for our pLCA coupled with *premise* assumptions is evaluated at 99.6 $t\,CO_2$-eq / MWh in 2025. However, a recent review by Gutsch and Leker (2022) on the GWP of 1st life battery pack manufacturing finds that, in more recent LCA studies, their EMF is often found to be lower than our assumed value. Taking studies conducted in 2019 and after, we can define a reasonable interval for the EMF of lithium-ion batteries ranging from 40 $t\,CO_2$-eq / MWh to 175 $t\,CO_2$-eq / MWh. Thus, by adapting the EMF of this technology in 2025 – as the expansion year taken into account in our pLCA closest to the time range of the reviewed studies and with the highest EMF for 1st life batteries – so that it varies in this range, we can investigate its influence on the resulting GWP difference induced by the deployment of V2G strategies. It shall be highlighted that solely the EMF for battery pack manufacturing is altered; the GHG emissions arising from the production of the battery and power electronics container remain identical.

Figure 4.18 shows the results of our sensitivity analysis. Thereby, Figure 4.18a portrays the total additional GWP impacts over the entire evaluated time frame in each scenario with respect to the EMF of the battery pack in 2025. Figure 4.18b illustrates the percentage of difference in total additional GWP impacts in *allST* with respect to *1st2nd* – negative percentages indicate GHG emission savings in a bidirectional charging context while positive percentages imply an increase in GHG emissions. Savings induced by the deployment of V2G services in the overall energy system's GWP are achieved if the total cumulative GWP impacts in *allST* are lower than those in *1st2nd* in Figure 4.18a, i. e. the percentage of difference



(a) Cumulative overall additional energy system GWP impacts in the *1st2nd* and *allST* with respect to the other scenario



(b) Difference rate in cumulative additional GWP impacts between *allST* and *1st2nd*

Figure 4.18 Sensitivity analysis on the EMF for GWP of 1st life battery packs in 2025

is negative in Figure 4.18b. This is the case for the entire studied range of battery packs EMFs, which comforts the findings of our pLCA. In the best case, within our differential point of view, about 30% of GHG emissions might be saved thanks to this measure, which is the case when considering a battery pack EMF of 175 t CO_2-eq / MWh. For a very low battery pack EMF of 40 t CO_2-eq / MWh, these savings are reduced to slightly more than 14%. In our reference EMF case of 99.6 t CO_2-eq / MWh, we are in an average impact savings situation. The sensitivity analysis reinforces our inference that a small advantage of bidirectional charging strategies on the GHG emissions of the energy system can be discerned in this thesis.

Chapter summary *A pLCA on the difference in overall energy system expansion brought forth by the deployment of bidirectional charging strategies has been conducted in this chapter. As a means of doing this, we have applied the framework elaborated in Chapter 3 on two ISAaR scenarios mirroring the object of study. Its environmental impacts have been calculated based on the savings and expenditures in capacity expansion and energy carrier consumption induced by this measure, most of them being occasioned by a large-scale application of BEV-based storage provision instead of stationary BESS. Regarding the difference in GWP, we identified a small reduction in GHG emissions in the event of V2G strategy deployment. This reduction is more noticeable when looking at the savings in metal resources. These savings are principally due to the avoidance of stationary battery manufacture. Still, our elaborated results are sensitive to assumptions and model results because of the small divergences induced by the measure with respect to the energy system in its entirety.*

5 Conclusion

By this point, we have presented and dealt with all considerations, proceedings, and inferences that lead to an investigation of the topic at hand and achieving the set objectives. Particularly, a methodology for the conception of an automated framework for the realization of a pLCA on the energy system difference induced by a given measure has been presented and subsequently applied to the flexibility option “bidirectional charging”. All these contemplations shall now be brought together to conclude this work.

Goal and structure of the chapter *This chapter aims to round off this thesis by summarizing its procedure and findings. In particular, as a first step, an answer shall be provided to the research questions elaborated in the introduction. Thereupon, limitations relative to the methodology, assumptions, and models used within this thesis shall be listed and discussed. Suggestions for an improvement of the framework in the future shall be given. We conclude this thesis with an outlook for further investigation of this topic.*

5.1 Findings

We present the main findings of this thesis by recalling and answering the research questions formulated at the beginning in Section 1.3.

Research question 1 How can the prospective life cycle assessment on the difference in the overall energy system expansion induced by the future deployment of a given measure be realized in an automated way?

This research question has been covered in Chapter 3, in which a framework relying on the conjunction of ESM results and pLCA methodology has been conceived. The particularity of the conducted pLCA lies in the differential point of view adopted for the scope of the assessment. Indeed, the computed environmental impact score reflects the endogenous repercussions on the energy system expansion induced by introducing a chosen future measure, technology, or policy. Thereby, ESM scenarios mirroring the measure to be investigated – i. e. whose only parameter difference consists in exactly this measure – need to be evaluated beforehand: the results then serve as input to the pLCA and, by extension, the automated framework. In our specific case, the framework relies on the FfE ESM ISAaR, which is based on an optimization of the overall system costs. After retrieving the results for both scenarios, the framework computes the difference in investments required for the future energy system expansion. The investments accounted for within the scope of the assessment comprise the construction of new generation and storage capacity as well as the supply and combustion of energy carriers for conversion purposes. An LCI of this difference is then set up by matching the investments with background pLCI processes taking into account future socioeconomic and technological developments. These processes are generated with the library *premise* on the basis of the LCI DB ecoinvent prior to the framework execution. The LCA software environment Brightway2 then automatically performs the LCIA for all desired impact categories. Figures produced by the framework can help the user in interpreting the obtained results.

Research question 2 In the future, will there be an environmental advantage from the energy system’s perspective to using mobile EV storage by spreading out bidirectional charging over using alternative battery storage?

This research question has been covered in Chapter 4 by applying the conceived automated framework to the flexibility option "bidirectional charging". Thereby, the scope of this thesis resides in the assessment of the measure-related difference in future-oriented life cycle environmental impacts of the German energy system expansion pathway towards reaching carbon neutrality in 2045 in Germany and 2050 on an EU level while aiming to comply with the Paris Agreement. In general, divergences in energy system investments in Germany for achieving this goal are marginal with respect to the overall energy system. Indeed, investment savings and expenditures are on the order of a hundredth of the overall energy system investments and result from the ISAaR cost optimization. Hence, results are not representative of the absolute impacts of the German energy system expansion but shall be seen as an indicator of impact disparities relative to a large-scale V2G deployment. It has been found that a total of 14.9 Mt CO_2-eq and 41.1 Mt Fe-eq may be saved by introducing V2G technologies in the German energy system. This corresponds to a 22% and 56% reduction in GHG emissions and metal resource utilization, respectively, within our differential point of view. It has been shown that the impact savings and expenditures induced by deploying bidirectional charging strategies fluctuate strongly depending on the evaluated expansion year and the disparities in the construction of new capacity. From a big-picture point of view, GWP savings remain relatively small, while an advantage in limiting MDP impacts is observable. Nonetheless, it shall be recalled that this inference only concerns two environmental impact categories and is subject to the assumptions and limitations of the pLCA. Supplementary economic, societal, and environmental advantages and drawbacks of implementing this technology should be taken into account for decision-making.

Research question 3 Which additionally built facilities within the deployment of the flexibility option "bidirectional charging" have particularly high environmental impacts? Which impacts can be saved by introducing this measure?

This research question has likewise been covered in Chapter 4. Within the framework application to the flexibility option "bidirectional charging", we found that, in accordance with the investigated topic and scenarios, the investment differences majorly lie in the technology used for short-term storage provision. Thus, in the case of bidirectional charging, the vast majority of short-term storage capacity is provided through mobile BEVs due to the cost advantage of this technology. On the other hand, if the model does not have the possibility to upgrade BEVs to be capable of V2G, stationary 1st and 2nd life batteries are used for supplying this kind of storage. Again, 2nd life batteries are preferred due to their lower cost. The EMF associated with the manufacture of 1 MWh of each technology plays a critical role in the obtained LCIA results. Thereby, we found that stationary BESS fabrication has an especially high EMF for both GWP and MDP due to a high need for polluting raw metals for the battery and power electronics containers. The ancillary manufacture of battery packs makes 1st life stationary BESS expansion even more environmentally harmful in this regard. For the deployment of V2G strategies, the additional ICT requirements in charging infrastructure induced by this upgrade have been assessed; their EMF is relatively low and could be further reduced by sharing infrastructures between BEV owners. On the whole, it has been found that 31.5 Mt CO_2-eq and 61.4 Mt Fe-eq may be saved thanks to the avoidance of stationary BESS manufacturing, but, at the same time, deploying V2G charging infrastructure has an environmental cost of 5.8 Mt CO_2-eq and 17.9 Mt Fe-eq.

Other impact divergences are brought forth by proportionally low divergences in the overall energy system expansion and are, for the most part, compensated over the entire time frame of the assessment. Nonetheless, two major impact divergences are worth mentioning. First, within our differential point of view, a considerable amount of GHG emissions are saved due to a slightly lower need for natural gas and biomass combustion and a marginally increased recourse to CCS in the case of V2G deployment. On the other hand, a significant amount of GHG emissions arise from a higher hydrogen storage capacity expansion. These divergences can be mainly attributed to the cost optimization used for evaluating the energy system expansion and the higher flexibility provided by mobile BEV storage over stationary BESS.

5.2 Limitations

The elaborated results are subject to a non-negligible amount of limitations due to data availability, assumptions, and low scenario divergences, among others. We shall list the limitations of our work in the following:

- ISAaR scenario results have been adopted as they are and do not belong to the contributions of this thesis. Hence, given the time limitations, a full interpretation and validation of these results lies out of the scope of this work. Indeed, most divergences are explained by the underlying ISAaR cost optimization, and a more in-depth look at the model would be necessary to meaningfully track their cause. Likewise, a critical reflection on the scenario results is out of the scope of this thesis.
- Echoing the previous point, no divergences in the overall BEV fleet induced by the deployment of bidirectional charging strategies have been foreseen in ISAaR, and, accordingly, BEV life cycle impacts have been left out of the scope of the pLCA. Should these assumptions, however, not be valid in other future pathways, then environmental impacts related to V2G implementation would be affected. Likewise, in this pLCA, it has been hypothesized that one bidirectional charging infrastructure is associated with one BEV and that no sharing of infrastructures takes place. This is probably not realistic in the future and could be taken into account in further studies for more precise results.
- Due to the limitations of the ecoinvent DB, the end-of-life treatment of facilities and energy carriers has not been taken into account in the pLCA, despite the environmental challenges associated with waste generation and circular economy. More specifically, some generic ecoinvent processes used for background modeling include this life phase, while others do not. However, due to time constraints, these divergences have not been addressed within the scope of this thesis, hence creating a bias in the obtained impact results. A suggestion for future improvement of the automated framework thus lies in the accurate integration of this life phase in the pLCA.
- In accordance with the previous point, we highlight the limitations of using generic ecoinvent processes for the pLCA realization, which, per definition, do not account for the specific characteristics and needs of individual plants. Moreover, due to data availability in ecoinvent, the regional scope of those processes is often not adapted to conditions in Germany, which includes particularities in the energy mix, local material availability, or transport distances. In general, all impact assessments are subject to measure and characterization uncertainties – it might be interesting to investigate the extent of those uncertainties in future work.
- Input data used for the application of this framework are projections of the future considering certain trends and model structures. They do not in any way represent actual future developments but mirror a possible scenario pathway of society. Thus, both ISAaR and IAM model results are determined within the limitations of the considered scenario, and, per extension, this is also the case for the pLCA impact scores. Again, a critical discussion or interpretation of the scenario assumptions and outcomes lies beyond the scope of this thesis. Furthermore, it shall be emphasized that, despite paying attention to the convergence of ISAaR and IAM scenario trends, these have been conceived separately, and, thus, a complete congruence cannot be achieved, which further creates a bias in our pLCA.
- ISAaR scenario results have only been evaluated in five-year steps and, as a consequence, do not account for annual endogenous variations within these steps. For estimating the impact difference arising over the entire considered time frame, we have hypothesized that investments in the energy system expansion do not vary within individual steps, thus, assuming a uniform impact distribution in each step. This is not realistic and, therefore, biases scores on the overall time frame.
- Due to the small ISAaR scenario divergences induced by the bidirectional charging measure, pLCA results are even more sensitive to assumptions and ecoinvent process uncertainties, thus stressing the limitations mentioned above. Additionally, those marginal disparities have non-negligible weight in the overall environmental impact balance.

5.3 Outlook

The major value added of this work lies in the automated framework conception, which can be applied to further ends in the future. Thereby, any two ISAaR scenarios mirroring a desired measure or pathway may serve as input to the framework. However, due to the time constraints of the thesis, an ecoinvent matching has solely been carried out for the ISAaR technologies featured in the energy system divergence of our use case. Thus, in the future, the framework could be extended to provide a matching to all technologies modeled in ISAaR. Moreover, as already mentioned, further work could be put into the accurate evaluation of the energy system's end-of-life.

We conclude this thesis by recalling the system boundary limitations of the findings resulting from the framework application to the deployment of bidirectional charging strategies. Indeed, the highlighted environmental advantages only hold for the analysis of the energy supply sector expansion. In the future, this system boundary might be extended to include divergences in the energy distribution or FEC. Moreover, further impact categories might be studied to account for a wider variety of environmental consequences. Lastly, this study has been exclusively conducted from an energy system's perspective, yet could, in the future, be put into relation with environmental impact divergences induced by bidirectional charging strategies related to the automotive perspective.

Chapter summary *In this chapter, we have highlighted the conception of the automated framework as being a major contribution of this thesis, which may be further used and extended in the future. Our second major contribution lies in the application of the framework to the study of the future-oriented environmental impacts of bidirectional charging strategies from an energy system's perspective. Addressing the identified research gap, our study covers the repercussions of this measure on the endogenous power plant park expansion for all energy carriers. Results are to be considered within the specified limitations.*

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Appendix

A.1 Appendix 1 – Life Cycle Inventory

A.1.1 Matching Between ISAaR and Ecoinvent

Acronym	Meaning
DE	Germany
RER, EUR	Europe
RoW	Rest of the World
GLO, World	World

Table A.1 Ecoinvent process location acronyms sorted by ascending aggregation level

Power plant type	Lifetime [a]
Battery	15
Battery 2nd Life	15
Electrolysis	30
EMob - bidirectional charging	15
EMob - smart charging	15
Gas Turbine (H2 Ready)	25
Heating Rod	21
Heatpump	20
Hydrogen Storage	40
Offsite Solar	25
Power-to-Methane	30
Rooftop Solar	25
Slack Power Generation/Consumption	–
Thermal Storage	70
Wind Onshore	25
Wind Offshore	25

Table A.2 Lifetime of individual ISAaR power plant types. This only includes ISAaR technologies relevant to the evaluation of V2G strategies.

ISAaR technology key	ISAaR technology name	Ecoinvent process name	Ecoinvent region	Ecoinvent unit	Generation capacity [MW]	Storage capacity [MWh]	Share 2025	Share 2030	Share 2035	Share 2040	Share 2045	Share 2050
2	Battery	import	DE	megawatt hour	–	1	1	1	1	1	1	1
99	Battery 2^{nd} Life	import	DE	unit	–	1.236	1	1	1	1	1	1
15	Electrolysis	electrolyzer, PEM	GLO	unit	1	–	1	1	1	1	1	1
93	EMob - bidirectional charging	import	DE	unit	–	0.07	1	1	1	1	1	1
94	EMob - smart charging	import	DE	unit	–	0.07	1	1	1	1	1	1
96	Gas Turbine (H2Ready)	gas power plant construction, 100MW electrical	RER	unit	100	–	1	1	1	1	1	1
43	Heating Rod	auxiliary heating unit production, electric, 5kW	RoW	unit	0.005	–	1	1	1	1	1	1
70	Heatpump	heat pump production, brine-water, 10kW	RoW	unit	0.01	–	1	1	1	1	1	1
71	Hydrogen Storage	compressed air energy storage plant construction, adiabatic, 150 MW electrical	RER	unit	–	19200	0.95	0.95	0.95	0.95	0.95	0.95
71	Hydrogen Storage	high pressure hydrogen storage tank	GLO	kilogram	–	0.0333	0.05	0.05	0.05	0.05	0.05	0.05
73	Offsite Solar	photovoltaic open ground installation, 570 kWp, single-Si, on open ground	RER	unit	0.57	–	0.52	0.52	0.52	0.52	0.52	0.52

Table A.3 Matching table for assessing the power plant's construction phase (part 1). This only includes ISAaR technologies relevant to the evaluation of V2G strategies.

ISAaR technology key	ISAaR technology name	Ecoinvent process name	Ecoinvent region	Ecoinvent unit	Generation capacity [MW]	Storage capacity [MWh]	Share 2025	Share 2030	Share 2035	Share 2040	Share 2045	Share 2050
73	Offsite Solar	photovoltaic open ground installation, 570 kWp, multi-Si, on open ground	RER	unit	0.57	–	0.43	0.43	0.43	0.43	0.43	0.43
73	Offsite Solar	photovoltaic open ground installation, 570 kWp, CdTe, on open ground	RER	unit	0.57	–	0.025	0.025	0.025	0.025	0.025	0.025
73	Offsite Solar	photovoltaic open ground installation, 570 kWp, CIS, on open ground	RER	unit	0.57	–	0.025	0.025	0.025	0.025	0.025	0.025
44	Power-to-Methane	Sabatier reaction methanation unit	RER	unit	0.025	–	1	1	1	1	1	1
74	Rooftop Solar	photovoltaic slanted-roof installation, 3kWp, single-Si, panel, mounted, on roof	RER	unit	0.003	–	0.52	0.52	0.52	0.52	0.52	0.5
74	Rooftop Solar	photovoltaic slanted-roof installation, 3kWp, multi-Si, panel, mounted, on roof	RER	unit	0.003	–	0.43	0.43	0.43	0.43	0.43	0.43
74	Rooftop Solar	photovoltaic slanted-roof installation, 3 kWp, CdTe, panel, mounted, on roof	RER	unit	0.003	–	0.025	0.025	0.025	0.025	0.025	0.025
74	Rooftop Solar	photovoltaic slanted-roof installation, 3kWp, CIS, panel, mounted, on roof	RER	unit	0.003	–	0.025	0.025	0.025	0.025	0.025	0.025
58	Slack Power Generation/ Consumption	missing	–	–	–	–	–	–	–	–	–	–
54	Thermal Storage	thermal storage system construction, solar tower power plant, 20 MW	RoW	unit	–	440	1	1	1	1	1	1

Table A.4 Matching table for assessing the power plant's construction phase (part 2). This only includes ISAaR technologies relevant to the evaluation of V2G strategies.

ISAaR technology key	ISAaR technology name	Ecoinvent process name	Ecoinvent region	Ecoinvent unit	Generation capacity [MW]	Storage capacity [MWh]	Share 2025	Share 2030	Share 2035	Share 2040	Share 2045	Share 2050
65	Wind Offshore	wind power plant construction, 2MW, offshore, moving parts	GLO	unit	2	–	1	1	1	1	1	1
65	Wind Offshore	wind power plant construction, 2MW, offshore, fixed parts	GLO	unit	2	–	1	1	1	1	1	1
64	Wind Onshore	wind power plant construction, 800kW, fixed parts	GLO	unit	0.8	–	0.07	0.07	0.07	0.07	0.07	0.07
64	Wind Onshore	wind power plant construction, 800kW, moving parts	GLO	unit	0.8	–	0.07	0.07	0.07	0.07	0.07	0.07
64	Wind Onshore	wind turbine construction, 2MW, onshore	GLO	unit	2	–	0.6	0.56	0.56	0.47	0.39	0.39
64	Wind Onshore	wind turbine construction, 4.5MW, onshore	GLO	unit	4.5	–	0.4	0.44	0.44	0.53	0.61	0.67

Table A.5 Matching table for assessing the power plant's construction phase (part 3). This only includes ISAaR technologies relevant to the evaluation of V2G strategies.

ISAaR technology key	ISAaR technology name	Ecoinvent process name	Ecoinvent region	Ecoinvent unit	Conversion factor	Facility construction	Share 2025	Share 2030	Share 2035	Share 2040	Share 2045	Share 2050
18	Biomass Imports	market for biogas	RoW	cubic meter	158.38	–	1	1	1	1	1	1
69	CCS Direct Air Capture	import	EUR	kilogram	1000	–	1	1	1	1	1	1
67	Green Methane Imports	import	World	kilogram	75.79	–	1	1	1	1	1	1
50	Hard Coal	Hard coal, burned in power plant/PC, no CCS	RER	megajoule	3600	market for hard coal power plant	1	1	1	1	1	1
9	Lignite	Lignite, burned in power plant/IGCC, no CCS	RER	megajoule	3600	Lignite IGCC power plant 450MW	1	1	1	1	1	1
52	Miscellaneous Fossil Fuels	diesel, burned in diesel-electric generating set	RER	megajoule	3600	diesel-electric generating set production 10MW	1	1	1	1	1	1
19	Natural Gas Imports	natural gas, burned in gas turbine	DE	megajoule	3600	market for gas turbine, 10MW electrical	1	1	1	1	1	1

Table A.6 Matching table for assessing the power plant's use phase. This only includes ISAaR technologies relevant to the evaluation of V2G strategies.

A.1.2 Manual Ecoinvent Process Creation

Smart charging infrastructure

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, emob, mME	emob, mME	1	unit	DE	production
–	polycarbonate production	polycarbonate	0.29	kilogram	RER	techno-sphere
–	acrylonitrile-butadiene-styrene copolymer production	acrylonitrile-butadiene-styrene copolymer	0.24	kilogram	RER	techno-sphere
–	glass fibre production	glass fibre	0.12	kilogram	RER	techno-sphere
–	market for steel, low-alloyed	steel, low-alloyed	0.15	kilogram	EUR	techno-sphere
–	market for copper, cathode	copper, cathode	0.035	kilogram	GLO	techno-sphere
–	iron-nickel-chromium alloy production	iron-nickel-chromium alloy	0.035	kilogram	RER	techno-sphere
–	tin production	tin	0.035	kilogram	RoW	techno-sphere
–	electronic component production, active, unspecified	electronic component, active, unspecified	0.065	kilogram	GLO	techno-sphere
–	electronic component production, passive, unspecified	electronic component, passive, unspecified	0.065	kilogram	GLO	techno-sphere
–	liquid crystal display production, minor components, auxilliaries and assembly effort	liquid crystal display, minor components, auxilliaries and assembly effort	0.02	kilogram	GLO	techno-sphere
–	electricity, high voltage, production mix	electricity, high voltage	2.92	kilowatt hour	DE	techno-sphere

Table A.7 Manual ecoinvent process creation table for mME as in Wohlschlager et al. (2022)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, emob, wallbox AC	emob, wallbox AC	1.00	unit	RER	production
–	polyester resin production, unsaturated	polyester resin, unsaturated	0.03	kilogram	RER	techno-sphere
–	acrylonitrile-butadiene-styrene copolymer production	acrylonitrile-butadiene-styrene copolymer	0.25	kilogram	RER	techno-sphere
–	reinforcing steel production	reinforcing steel	0.04	kilogram	Europe without Austria	techno-sphere
–	iron-nickel-chromium alloy production	iron-nickel-chromium alloy	0.01	kilogram	RER	techno-sphere
–	electronics production, for control units	electronics, for control units	1.21	kilogram	RER	techno-sphere
–	metal working, average for chromium steel product manufacturing	metal working, average for chromium steel product manufacturing	2.79	kilogram	RER	techno-sphere
–	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing	0.04	kilogram	RER	techno-sphere
–	market for cable, three-conductor cable	cable, three-conductor cable	0.20	meter	GLO	techno-sphere
–	polyethylene pipe production, corrugated, DN 75	polyethylene pipe, corrugated, DN 75	0.07	meter	RER	techno-sphere

Table A.8 Manual ecoinvent process creation table for wallbox AC as in Wohlschlager et al. (2022)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, emob, wallbox DC	emob, wallbox DC	1.00	unit	RER	production
–	polyester resin production, unsaturated	polyester resin, unsaturated	0.07	kilogram	RER	techno-sphere
–	acrylonitrile-butadiene-styrene copolymer production	acrylonitrile-butadiene-styrene copolymer	0.52	kilogram	RER	techno-sphere
–	reinforcing steel production	reinforcing steel	0.08	kilogram	Europe without Austria	techno-sphere
–	iron-nickel-chromium alloy production	iron-nickel-chromium alloy	0.03	kilogram	RER	techno-sphere
–	electronics production, for control units	electronics, for control units	16.00	kilogram	RER	techno-sphere
–	metal working, average for chromium steel product manufacturing	metal working, average for chromium steel product manufacturing	5.85	kilogram	RER	techno-sphere
–	metal working, average for steel product manufacturing	metal working, average for steel product manufacturing	0.08	kilogram	RER	techno-sphere
–	market for cable, three-conductor cable	cable, three-conductor cable	0.41	meter	GLO	techno-sphere
–	polyethylene pipe production, corrugated, DN 75	polyethylene pipe, corrugated, DN 75	0.15	meter	RER	techno-sphere

Table A.9 Manual ecoinvent process creation table for wallbox DC as in Wohlschlager et al. (2022)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, emob, smart charging	emob, smart charging, infrastructure	1	unit	DE	production
mME	literature, emob, mME	emob, mME	1	unit	DE	techno-sphere

Table A.10 Manual ecoinvent process creation table for unidirectional controlled charging adapted from Wohlschlager et al. (2022)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, emob, bidirectional charging	emob, bidirectional charging, infrastructure	1	unit	DE	production
mME	literature, emob, mME	emob, mME	1	unit	DE	techno-sphere
Wallbox DC	literature, emob, wallbox DC	emob, wallbox DC	1	unit	RER	techno-sphere
Wallbox AC	literature, emob, wallbox AC	emob, wallbox AC	-1	unit	RER	techno-sphere

Table A.11 Manual ecoinvent process creation table for bidirectional charging adapted from Wohlschlager et al. (2022)

Stationary batteries

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, battery, Li-ion, repurposing	battery, Li-ion, repurposed	1	kilogram	DE	production
–	market for electricity, medium voltage	electricity, medium voltage	1	kilowatt hour	DE	techno-sphere
–	market for transport, freight, sea, container ship	transport, freight, sea, container ship	2	ton kilometer	GLO	techno-sphere
–	market for transport, freight, lorry >32 metric ton, EURO5	transport, freight, lorry >32 metric ton, EURO5	0.35	ton kilometer	RER	techno-sphere
–	market for precious metal refinery	precious metal refinery	1.90E-08	unit	GLO	techno-sphere

Table A.12 Manual ecoinvent process creation table for lithium-ion battery repurposing as in Schulz-Mönninghoff et al. (2021)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, BESS, battery container	BESS, battery container	1	unit	RER	production
–	market for copper-rich materials	copper-rich materials	574	kilogram	GLO	techno-sphere
–	market for ventilation control and wiring, central unit	ventilation control and wiring, central unit	2	unit	GLO	techno-sphere
–	market for intermodal shipping container, 40-foot	intermodal shipping container, 40-foot	1	unit	GLO	techno-sphere
–	market for fibreboard, hard	fibreboard, hard	0.47	cubic meter	RER	techno-sphere
–	market for steel, low-alloyed, hot rolled	steel, low-alloyed, hot rolled	4161.8	kilogram	GLO	techno-sphere
–	market for stone wool	stone wool	860	kilogram	GLO	techno-sphere
–	market for chromium steel pipe	chromium steel pipe	125	kilogram	GLO	techno-sphere
–	market for ultraviolet lamp	ultraviolet lamp	5	unit	GLO	techno-sphere
–	market for welding, arc, steel	welding, arc, steel	559.4	meter	GLO	techno-sphere
–	market for alkyd paint, white, without water, in 60% solution state	alkyd paint, white, without water, in 60% solution state	10.36	kilogram	RER	techno-sphere
–	transport, freight, lorry 3.5-7.5 metric ton, EURO5	transport, freight, lorry 3.5-7.5 metric ton, EURO5	3929.25	ton kilometer	RER	techno-sphere
–	market for controller, for electric scooter	controller, for electric scooter	50	kilogram	GLO	techno-sphere
–	market for power adapter, for laptop	power adapter, for laptop	114	unit	GLO	techno-sphere
–	market for cable, data cable in infrastructure	cable, data cable in infrastructure	20100	meter	GLO	techno-sphere
–	market for fan, for power supply unit, desktop computer	fan, for power supply unit, desktop computer	40	kilogram	GLO	techno-sphere

Table A.13 Manual ecoinvent process creation table for battery container as in Schulz-Mönninghoff et al. (2021)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, BESS, power electronics container	BESS, power electronics container	1	unit	RER	production
–	market for fan, for power supply unit, desktop computer	fan, for power supply unit, desktop computer	60	kilogram	GLO	techno-sphere
–	market for copper-rich materials	copper-rich materials	1219.72	kilogram	GLO	techno-sphere
–	market for ventilation control and wiring, central unit	ventilation control and wiring, central unit	2	unit	GLO	techno-sphere
–	market for intermodal shipping container, 40-foot	intermodal shipping container, 40-foot	1	unit	GLO	techno-sphere
–	market for fibreboard, hard	fibreboard, hard	0.47	cubic meter	RER	techno-sphere
–	market for steel, low-alloyed, hot rolled	steel, low-alloyed, hot rolled	1801.8	kilogram	GLO	techno-sphere
–	market for stone wool	stone wool	860	kilogram	GLO	techno-sphere
–	market for ultraviolet lamp	ultraviolet lamp	5	unit	GLO	techno-sphere
–	market for welding, arc, steel	welding, arc, steel	72.8	meter	GLO	techno-sphere
–	market for alkyd paint, white, without water, in 60% solution state	alkyd paint, white, without water, in 60% solution state	10.36	kilogram	RER	techno-sphere
–	transport, freight, lorry 3.5-7.5 metric ton, EURO5	transport, freight, lorry 3.5-7.5 metric ton, EURO5	3848	ton kilometer	RER	techno-sphere
–	market for controller, for electric scooter	controller, for electric scooter	20	kilogram	GLO	techno-sphere
–	market for cable, data cable in infrastructure	cable, data cable in infrastructure	1975	meter	GLO	techno-sphere
–	market for resistor, auxilliaries and energy use	resistor, auxilliaries and energy use	180	kilogram	GLO	techno-sphere
–	market for converter, for electric passenger car	converter, for electric passenger car	283.2	kilogram	GLO	techno-sphere
–	market for computer, laptop	computer, laptop	2	unit	GLO	techno-sphere
–	market for power adapter, for laptop	power adapter, for laptop	1	unit	GLO	techno-sphere

Table A.14 Manual ecoinvent process creation table for power electronics container as in Schulz-Mönninghoff et al. (2021)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, BESS, installation	BESS, installation	1	unit	RER	production
–	transport, freight, lorry 7.5-16 metric ton, EURO5	transport, freight, lorry 7.5-16 metric ton, EURO5	7287.65	ton kilometer	RER	techno-sphere
–	market for reinforcing steel	reinforcing steel	1000	kilogram	GLO	techno-sphere
–	market for concrete, normal	concrete, normal	20	cubic meter	RoW	techno-sphere

Table A.15 Manual ecoinvent process creation table for BESS installation as in Schulz-Mönninghoff et al. (2021)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, BESS, Li-ion	BESS, Li-ion	1	megawatt hour	DE	production
–	market for battery, Li-ion, NMC111, rechargeable, prismatic	battery, Li-ion, NMC111, rechargeable, prismatic	7021.28	kilogram	GLO	techno-sphere
Battery container	literature, BESS, battery container	BESS, battery container	0.809	unit	RER	techno-sphere
Power electronics container	literature, BESS, power electronics container	BESS, power electronics container	0.809	unit	RER	techno-sphere
Installation	literature, BESS, installation	BESS, installation	0.809	unit	RER	techno-sphere

Table A.16 Manual ecoinvent process creation table for 1st life BESS adapted from Schulz-Mönninghoff et al. (2021)

Reference Excel sheet	Exchange process name	Exchange product	Exchange amount	Exchange unit	Exchange location	Exchange type
–	literature, SLBESS, Li-ion	SLBESS, Li-ion	1	unit	DE	production
LIB repurposing	literature, battery, Li-ion, repurposing	battery, Li-ion, repurposed	12320	kilogram	DE	techno-sphere
Battery container	literature, BESS, battery container	BESS, battery container	1	unit	RER	techno-sphere
Power electronics container	literature, BESS, power electronics container	BESS, power electronics container	1	unit	RER	techno-sphere
Installation	literature, BESS, installation	BESS, installation	1	unit	RER	techno-sphere

Table A.17 Manual ecoinvent process creation table for 2nd life BESS adapted from Schulz-Mönninghoff et al. (2021)

A.2.3 Use-case Results

1st2nd	**Unit**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	MWh	0.7	116917.3	–	–	3634.4	–
Battery 2nd Life	MWh	1696.4	1009	27489.5	143483.1	96668.4	46444.5
Electrolysis	MW	–	–	1676.8	–	1643.6	–
Gas Turbine (H2Ready)	MW	–	2168.8	0.1	–	2249.4	85.1
Heating Rod	MW	927.3	737.6	–	–	–	24.2
Heatpump	MW	62.1	–	–	1.9	60.3	–
Hydrogen Storage	MWh	286.6	–	904773.6	–	–	–
Offsite Solar	MW	–	–	–	28899.4	–	–
Power-to-Methane	MW	–	–	–	1971.8	3.6	1861.8
Slack Power Generation/Consumption	MW	3926.9	–	42.8	–	–	–
Thermal Storage	MWh	–	30789.8	–	–	–	–
Wind Offshore	MW	–	–	104.1	–	–	–
Wind Onshore	MW	–	–	5693.4	–	–	–

Table A.18 Inventory of the additionally constructed capacity in the *1st2nd* scenario

1st2nd	**Unit**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Biomass	MWh	–	243761.3	794303.5	564644.4	372983	401040.5
CCS Direct Air Capture	t	–	–	–	–	15768	–
Green Methane	MWh	–	–	–	–	808459.6	–
Hard Coal	MWh	94867.7	–	–	–	–	–
Miscellaneous Fossil Fuels	MWh	–	8446.5	–	6149.1	–	0.5
Natural Gas	MWh	–	4061700	2894274.7	400811.1	–	–

Table A.19 Inventory of the additional energy carrier transactions allocated to the energy supply sector in the *1st2nd* scenario

allST	**Unit**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Biomass	MWh	3.1	–	–	–	–	–
CCS Direct Air Capture	t	–	–	–	–	–	251936
Green Methane	MWh	–	–	–	–	–	2841941.4
Hard Coal	MWh	80707.5	–	–	–	–	–
Lignite	MWh	1097978.9	–	–	–	–	–
Miscellaneous Fossil Fuels	MWh	4396.1	–	17145.7	–	1552.8	–
Natural Gas	MWh	489964.7	–	–	–	–	–

Table A.21 Inventory of the additional energy carrier transactions allocated to the energy supply sector in the *allST* scenario

allST	**Unit**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	MWh	–	–	–	0.1	–	1.9
Electrolysis	MW	–	–	–	1929.7	–	1281.8
EMob - bidirectional charging	MWh	70180.8	380141.1	338954.6	341581.8	532853.6	432953.9
EMob - smart charging	MWh	131.7	450158.5	0.7	5.5	349	1.4
Gas Turbine (H2Ready)	MW	344.3	–	–	6414.9	–	–
Heating Rod	MW	–	–	94.8	100	80.2	–
Heatpump	MW	–	63.6	1	–	–	64.4
Hydrogen Storage	MWh	–	909475.9	–	0.3	2523.2	2182576.8
Offsite Solar	MW	–	–	28899	–	–	–
Rooftop Solar	MW	–	–	–	–	0.1	0.3
Power-to-Methane	MW	–	–	1858.5	–	–	–
Thermal Storage	MWh	1390.4	–	9885.6	10214.3	1500	2755.8
Wind Offshore	MW	–	–	–	103.4	0.4	0.1
Wind Onshore	MW	–	–	–	3513.3	596.3	325.6

Table A.20 Inventory of the additionally constructed capacity in the *allST* scenario

A.2 Appendix 2 – Life Cyle Impact Assessment

	Global warming potential [kg CO_2-eq]						Metal depletion [kg Fe-eq]					
1st2nd	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	1.16E+05	1.69E+10	–	–	4.17E+08	–	2.08E+05	3.45E+10	–	–	1.06E+09	–
Battery 2nd Life	1.16E+08	5.87E+07	1.38E+09	6.55E+09	4.20E+09	1.94E+09	1.47E+08	8.57E+07	2.28E+09	1.17E+10	7.83E+09	3.74E+09
Electrolysis	–	–	4.37E+07	–	3.56E+07	–	–	–	4.51E+07	–	4.37E+07	–
Gas Turbine (H2Ready)	–	9.82E+07	4.29E+03	–	9.05E+07	3.35E+06	–	7.23E+07	3.28E+03	–	7.27E+07	2.74E+06
Heating Rod	1.28E+06	8.75E+05	–	–	–	2.16E+04	5.46E+05	4.35E+05	–	–	–	1.43E+04
Heatpump	8.62E+06	–	–	2.31E+05	7.25E+06	–	5.69E+06	–	–	1.69E+05	5.35E+06	–
Hydrogen Storage	2.40E+06	–	6.98E+09	–	–	–	1.88E+05	–	5.54E+08	–	–	–
Offsite Solar	–	–	–	1.86E+10	–	–	–	–	–	8.96E+09	–	–
Power-to-Methane	–	–	–	6.56E+07	1.16E+05	5.87E+07	–	–	–	4.71E+07	8.61E+04	4.46E+07
Thermal Storage	–	2.42E+08	–	–	–	–	–	2.74E+07	–	–	–	–
Wind Offshore	–	–	6.26E+07	–	–	–	–	–	3.08E+07	–	–	–
Wind Onshore	–	–	3.08E+09	–	–	–	–	–	2.14E+09	–	–	–

Table A.22 Impact score of the additionally constructed capacity in the *1st2nd* scenario

	Global warming potential [kg CO_2-eq]						**Metal depletion [kg Fe-eq]**					
allST	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Battery	–	–	–	1.19E+04	–	2.12E+05	–	–	–	2.92E+04	–	5.52E+05
EMob - bidirectional charging	3.88E+08	1.55E+09	1.01E+09	8.03E+08	1.15E+09	8.99E+08	5.97E+08	3.23E+09	2.88E+09	2.90E+09	4.51E+09	3.67E+09
EMob - smart charging	1.11E+05	2.71E+08	2.92E+02	1.71E+03	9.76E+04	3.78E+02	2.43E+05	8.32E+08	1.29E+03	1.02E+04	6.46E+05	2.59E+03
Electrolysis	–	–	–	4.41E+07	2.71E+07	–	–	–	–	5.16E+07	–	3.40E+07
Gas Turbine (H2Ready)	1.66E+07	–	–	2.65E+08	–	–	1.16E+07	–	–	2.08E+08	–	–
Heating Rod	–	–	9.85E+04	9.47E+04	7.30E+04	–	–	–	5.58E+04	5.89E+04	4.73E+04	–
Heatpump	–	8.37E+06	1.26E+05	–	–	7.67E+06	–	5.78E+06	8.99E+04	–	–	5.69E+06
Hydrogen Storage	–	7.26E+09	–	2.27E+03	1.90E+07	1.63E+10	–	5.79E+08	–	1.81E+02	1.57E+06	1.45E+09
Offsite Solar	–	–	2.02E+10	–	–	–	–	–	9.36E+09	–	–	–
Power-to-Methane	–	–	6.69E+07	–	–	–	–	–	4.44E+07	–	–	–
Rooftop Solar	–	–	–	–	5.83E+04	1.69E+05	–	–	–	–	7.44E+04	2.21E+05
Thermal Storage	1.16E+07	–	7.46E+07	7.50E+07	1.08E+07	1.96E+07	1.26E+06	–	8.55E+06	8.68E+06	1.27E+06	2.34E+06
Wind Offshore	–	–	–	5.83E+07	2.16E+05	5.17E+04	–	–	–	2.96E+07	1.12E+05	2.76E+04
Wind Onshore	–	–	–	1.82E+09	3.03E+08	1.66E+08	–	–	–	1.38E+09	2.45E+08	1.42E+08

Table A.23 Impact score of the additionally constructed capacity in the *allST* scenario

	Global warming potential [kg CO_2-eq]						Metal depletion [kg Fe-eq]					
1st2nd	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Biomass	–	2.49E+07	7.95E+07	5.58E+07	3.67E+07	3.93E+07	–	2.50E+05	8.04E+05	5.71E+05	3.86E+05	4.23E+05
CCS Direct Air Capture	–	–	–	–	-1.5E+07	–	–	–	–	–	1.61E+05	–
Green Methane	–	–	–	–	2.92E+07	–	–	–	–	–	1.22E+07	–
Hard Coal	3.63E+07	–	–	–	–	–	1.15E+05	–	–	–	–	–
Miscellaneous Fossil Fuels	–	2.63E+06	–	1.89E+06	–	1.53E+02	–	1.45E+04	–	1.52E+04	–	4.51E+00
Natural Gas	–	9.28E+08	6.59E+08	9.12E+07	–	–	–	2.91E+06	1.91E+06	2.46E+05	–	–

Table A.24 Impact score of the additional energy carrier transactions allocated to the energy supply sector in the *1st2nd* scenario

	Global warming potential [kg CO_2-eq]						Metal depletion [kg Fe-eq]					
allST	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Biomass	3.27E+02	–	–	–	–	–	3.22E+00	–	–	–	–	–
CCS Direct Air Capture	–	–	–	–	–	-2.4E+08	–	–	–	–	–	2.54E+06
Green Methane	–	2.56E-02	1.74E-02	5.79E-03	–	9.89E+07	–	8.75E-03	6.62E-03	2.35E-03	–	4.17E+07
Hard Coal	3.09E+07	–	–	–	–	–	9.81E+04	–	–	–	–	–
Lignite	4.39E+08	–	–	–	–	–	3.77E+05	–	–	–	–	–
Miscellaneous Fossil Fuels	1.38E+06	–	5.28E+06	–	4.76E+05	–	6.83E+03	–	3.16E+04	–	7.37E+03	–
Natural Gas	1.12E+08	–	–	–	4.40E-01	5.70E-01	3.73E+05	–	–	–	1.15E-03	1.43E-03

Table A.25 Impact score of the additional energy carrier transactions allocated to the energy supply sector in the *allST* scenario