Big Data for OPen innovation Energy Marketplace

Deliverable 9.3

Life cycle analysis

Document information

Deliverable nr	D9.3
Deliverable Name	Life cycle analysis
Version	5.0
Release date	25/10/2023
Dissemination level	Public
Status	Submitted
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This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under **Grant Agreement No 872525**.

Document history:

Version	Date of issue	Content and changes	Edited by
1.0	03/03/2023	First version	Dominik Huber
1.1	05/09/2023	Updated version	Dominik Huber
2.0	11/05/2020	Reviewed version	Maeva Lavigne Philippot
3.0	23/10/2023	Inclusion of first revision from reviewers	Dominik Huber
4.0	25/10/2023	Removal of comments and last small, minor changes	Dominik Huber
5.0	31/10/2023	Final version	Dominik Huber

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Deliverable beneficiaries:

WP / task
WP9
WP8

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Abbreviations and Acronyms

Acronym	Description
AD	Abiotic depletion for minerals and metals
ALCA	Attributional life cycle assessment
CC	Climate change
CEEP	Critical excess electricity produced
CLCA	Consequential life cycle assessment
CON	Conservative energy scenario for eastern Denmark in 2050
DK2	Bidding zone 2 containing the regions Hovedstaden and Sjælland
EoL	End-of-life
EV	Electric vehicle
GHG	Greenhouse gas
HV	High voltage
IDEAL	Energy scenario based on excess renewable energy sources for eastern Denmark in 2050
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LFP	Lithium iron phosphate ($LiFePO_4$) cathode active material with graphite anode active material
LIB	Lithium-ion batteries
LV	Low voltage
MV	Medium voltage
NMC	Lithium nickel manganese cobalt oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$) cathode active material with graphite anode active material
OPT	Optimistic energy scenario for eastern Denmark in 2050
PPT	Power plant
PV	Photovoltaic
RES	Renewable energy sources
V2G	Vehicle-to-grid

Executive summary

The objective of this report is to analyze potential environmental impacts of energy services provided by the BD4OPEM project. Towards this a life cycle assessment was performed for two services: *S5.4 EV to Grid* and *S8.2 Asset estimation optimization for microgrids*.

The first service is assessed using consequential life cycle assessment based on inputs obtained by an energy model for eastern Denmark in 2050. Five scenarios are defined to present the future energy system in Denmark in 2050: Two conservative (CON) and optimistic scenarios (OPT), where S5.4 is compared to conventional electric vehicle charging and one last scenario, capturing an exaggeration of renewable energy penetration in combination with S5.4. In general, in the energy scenarios based on a decline of future transportation and electricity demand combined with an increase in renewable energy sources, the provided service S5.4 reveals more beneficial compared to system where electric vehicles are charged regularly. Thus, in the OPT scenario providing S5.4, the climate change (CC) impact is 50.4 gCO_2eq/kWh whereas with dump charging the CC is 51.2 gCO_2eq/kWh in the same scenario. In the CON scenario, the dump charging shows with 52.0 gCO_2eq/kWh lower CC than when service S5.4 is introduced. To show the impact on the results due to the uncertainty contained in the ecoinvent database, a comparative Monte Carlo analysis is conducted. This analysis confirms the trends described above.

The second service used data provided by T4.5 of the BD4OPEM project representing degradation of a stationary battery storage. For the second service, an attributional life cycle assessment is applied. First, the environmental impact of battery degradation is presented per kWh of degraded capacity and second the impact of degradation is presented per kWh of battery capacity. Unsurprisingly, the environmental impact of degradation compared to the manufacturing impact is found to be comparably low. Based on a kWh capacity, including degradation shows increasing environmental impacts. For a battery with lithium iron phosphate (LiFePO4) cathode active material with graphite anode active material and a battery with lithium nickel manganese cobalt oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$) cathode active material with graphite anode active material, considering a 40% degradation over its lifetime resulted in respectively a 19% and 20% increase of CC per kWh capacity.

Future research can continue to investigate in the following parts: first, more research effort is required to fully understand the impact of service 5.4 on the long-term marginal energy supply. Thus, the hourly electricity supply in the future should

be assessed, especially when evaluating services such as S5.4 depending on the impact of the hourly supply mix. This, however, might require new models and a modification in the research approach. Second, the asset degradation could be contextualized and applied in a specific case study. Third, further research is needed to understand the environmental cost of the IT infrastructure of projects like BD4OPEM.

1 Introduction

In order to become climate neutral by 2050, the European Union (EU) formulated the European Green Deal, in which they committed to the objective of no net emissions of greenhouse gas (GHG) by 2050. In 2021, the energy supply accounted for roughly 25% percent of GHG emissions in Europe (Figure 1). Therefore, one important pilar is to decarbonize the European energy system. Besides the integration of renewable energy carriers into the existing energy system, the clean energy transition also aims at a fully integrated, interconnected and digitalized EU energy market.

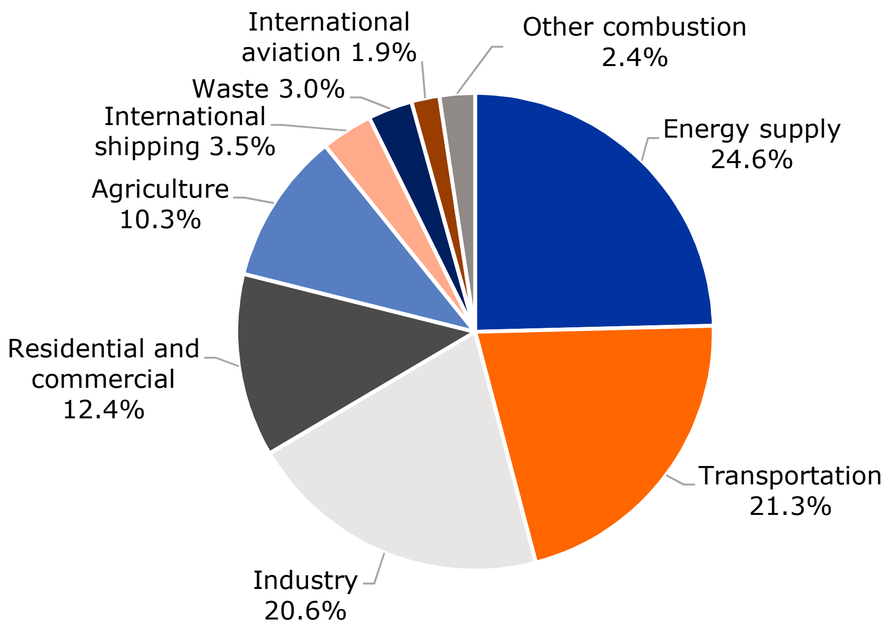

Figure 1: Distribution of greenhouse gas emissions in the European Union (EU-27) in 2021, by sector (source: Statista)

The Big Data for OPen innovation Energy Marketplace (BD4OPEM) project aims to develop an open energy marketplace offering innovative AI-based services, to enable the efficient management of energy distribution grids and associated assets. Overall, 18 different services have been developed within this project, covering operation and maintenance, fraud detection, flexibility and demand response, trading, planning and monitoring. The exploitation and business model work package foresees to conduct a life cycle assessment (LCA) of the project. The LCA methodology allows to identify environmental impacts of products and services and has been broadly applied to various energy systems. It is a holistic approach, considering raw material extraction, component manufacturing, use and end-of-life stage. The data required to conduct a

LCA, the life cycle inventory (LCI) data, is described as particularly time-consuming and data-intensive task [1].

The LCA methodology for the BD4OEPM project can be applied from two perspectives: On one site, the environmental impact of the computing the services including the required infrastructure such as the computers, data transmission and the cloud storage can be evaluated.

On the other hand, the BD4OPEM services themselves can be assessed. This evaluation would help stakeholders of the BD4OPEM marketplace which potential environmental impacts they would introduce if operationalizing the suggested service. Conducting a LCA for the BD4OPEM services, however, brings along various challenges: all provided services propose changes in an energy system, with an operationalization and installation period exceeding the timeline of this project. Thus, data collection for a potential future energy system cannot be obtained because the system is hypothetical. This problem can be overcome by using approximations and simulation tools for future energy systems, such as for example EnergyPLAN, TIMES model, etc. Additionally, the services could be applied to every given location, making the selection of a geographical system boundaries with a given energy layout difficult.

This deliverable will focus on the evaluation of the different services. Due to the temporal restriction of T9.3 and the previously described challenges of evaluating every single service, conducting a LCA for all services of the BD4OPEM project is not feasible or optimal. Thus the focus is on the service "S5.4 EV to Grid" and "S8.2 Asset estimation optimization for microgrids" and will be assessed in detail in this deliverable. The objective of assessing those two services is not to determine detailed GHG emissions of a particular site, but it is to understand the potential overall environmental impact of introducing such a service through the BD4OPEM marketplace and providing an indication of the potential impact the BD4OPEM marketplace can have in the future.

2 State-of-the-art literature

Since the entry of the electric vehicles (EV) in the mass market in the last decade, substantial research effort is dedicated to apply the LCA methodology to EVs in order to understand their environmental impacts [2]. Many studies aim to understand the environmental advantage of an EV over other drivetrain technologies [2]–[4]. Over the time, those studies enhanced their level of details to increase their reliability and to represent reality as good as possible, by introducing a range-based assessment to include variability in LCA of EVs [5]. Additionally, the LCA studies of EVs are applied in different countries in order to cover the environmental impact during the use stage [6]. At the same time, many LCA studies on the environmental impacts of the battery are published. The first and most well-known studies containing primary LCI data published are from Zackrisson et al. (2010), Majeau-Bettez et al. (2011) and Ellingsen et al. (2013) [7]–[9], which are until now frequently used as a reference for modelling mobile battery storage. Since those studies were published, more and more papers have occurred evaluating different battery chemistries, impact categories, use stage assumptions, system boundaries etc. A comprehensive overview of LCA studies on lithium-ion batteries (LIB) is provided by a review published by Peters et al. (2018), where they analyzed 79 different studies and summarized their results [10]. They highlight a great variance in GHG emissions even though the LCI data originate mostly from the same studies and found the average GHG emission for the battery production of various chemistries is 110 kg CO_2eq per kWh storage capacity. More recently, research on LCA of EVs is dedicated to understand the environmental impact of future electricity mix and different end-of-life management, giving the traction batteries a second-life and investigating in new materials in the battery [11]–[13]. All of those studies focus on EVs or their traction batteries and all studies are conducted from an attributional LCA (ALCA) perspective. Consequential LCA (CLCA) studies of EV or their batteries are much less frequently assessed. To studies are in particular relevant for this deliverable: Rovelli et al. (2021) conducted a CLCA for EV and investigated in the impact of the use phase applying an energy system model and CLCA [14]. Zhao and Baker (2022) studied the environmental impacts applying a CLCA of introducing mobile batteries as grid storage [15]. A summary of the existing literature on EVs is presented in Table 1.

In summary, CLCA studies of EV are only limited available. One of the two published studies uses an energy modelling software, the EnergyPLAN to simulate the energy system. Even though it does use an energy system software, it does not investigate into vehicle-to-grid (V2G) service. The second available publication does consider

V2G by using the EV as a mobile grid storage. One shortcoming though is the absence of an energy system model [15]. Instead, only annual electricity production projections are used.

Study object	System focus		LCA approach	Literature
EV	Transport	Vehicle	ALCA	[2], [5], [16], [6]–[13]
EV	Transport	Vehicle	CLCA	[14]
V2G	Transport Electricity	Energy system	CLCA	[15]

Table 1. Literature overview of existing LCA studies on EV taking into account different system perspectives and LCA approaches.

Hence, to the authors knowledge, no study exists that uses an energy system model to study the environmental impact of V2G EV applying a CLCA methodology. Therefore, this deliverable investigates for the first time to identify the environmental consequences of a future energy system including EV as a mobile grid storage. Thus, this deliverable will answer the following questions:

1. How can future scenarios for an energy system in 2050 be described?
2. What is the annual electricity production in 2050 of different scenarios?
3. What is the impact of V2G on the energy system in 2050?
4. What is the climate change and mineral resource depletion of the corresponding scenarios?
5. How much electricity will be discharged from EV and fed back to the grid?

Next to LCA of an entire EV, the evolution of the battery capacity during the battery's lifetime can be further analyzed. The battery of an EV is considered to reach its end-of-life (EoL) once its initial capacity reached 80% [17], while this value could be lower for stationary storage due to less extensive cycling, e.g. 60% [18]. It is noteworthy that the inclusion of degradation in an LCA itself does not require additional resource consumption. However, including the degradation does influence the energy that can be discharged from the battery. Consequently, when the environmental impacts of batteries are presented per kWh discharged, impacts are likely to increase as less electricity can be discharged due to the decrease in charging capacity. Battery degradation in an LCA can be considered as a linear degradation of capacity taking into account the difference between initial and remaining capacity at the end of the batteries lifetime [18]–[20]. The linear degradation can be linked to assuming the same cycling over the batteries lifetime, which is a simplification of real-life conditions. Alternatively, more dynamic degradation models can be included to obtain a more realistic degradation and more precise discharged electricity. However, this is not yet common practice in LCA studies of batteries. Hen et al. (2023) determines the cycling of the battery by considering a semi-empiric degradation model [21]. The research on understanding battery degradation, the identification of the right parameters to determine degradation and building degradation models out of it, is still in its infancy. Thus, it is not surprising that if degradation is considered in an LCA of batteries, most frequently linear degradation is assumed.

Thus, as a second part, this deliverable will investigate in the following questions:

1. Based on given degradation models, how will the CC impact per kWh storage capacity change compared to not including any degradation?
2. Quantified as lost battery capacity, how much are the degradation impacts compared to the manufacturing impacts?

3 Material and methods

3.1 Goal and scope

The goal of this deliverable is to conduct an LCA for two energy services developed within the BD4OPEM project in order to highlight associated potential environmental impacts of those services. LCA methodology was chosen as it is a well-recognized method for evaluating environmental impacts of a product or service. In general, two different LCA approaches can be distinguished: the ALCA represents a methodology which aims to understand the flow of environmental impacts within a given timeframe. It is a model, where input and output data are assigned to the function of the system [22]. Thus, the ALCA is also described as an accounting methodology. Next to the ALCA, there is the CLCA. The CLCA is described as methodology which investigates to understand how environmental impacts change due to a change in demand [22].

As two independent and completely different BD4OPEM services are assessed, a CLCA will be applied to reveal the environmental impacts of service "S5.4 EV to Grid" in order to understand the changes in the energy system that is caused by providing such a service. A CLCA is chosen to evaluate this service as the environmental impacts of an energy system where EV provide V2G service and an energy system where they do not provide such services. To model the energy system, future scenarios are built using the EnergyPLAN software. The functional unit for S5.4 is 1 kilowatt hour (kWh) of electricity delivered by the eastern Danish energy system in 2050. The assessment will be conducted for the eastern region of Denmark, including Hovedstaden and Sjælland. A cradle-to-gate approach comprising raw material extraction, component manufacturing, installation and use is selected. Multifunctional processes will be included using system expansion.

For the service "S8.2 Asset estimation optimization for microgrids" an ALCA will be conducted. Following Task 4.5 of the BD4OPEM project, which aims at quantifying degradation costs of stationary battery storage, the aim of this evaluation is to provide an environmental degradation cost of a stationary battery. Two batteries are selected as the chemistry of the battery used in the optimization is unknown. Thus, two common battery chemistries of stationary LIBs are evaluated and an environmental degradation cost will be calculated. The selected battery chemistries of the two LIBs are lithium iron phosphate ($LiFePO_4$) cathode active material (LFP) and lithium nickel manganese cobalt oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$) cathode active material (NMC) and both LIBs with graphite anode active material (NMC) [18]. Similar to service 8.2, this deliverable calculates the environmental cost of degradation. The functional unit is therefore in percentage of initial capacity loss. For this service, a cradle-to-gate approach is selected. Multifunctional processes will be assessed applying a physical allocation. Figure 2 summarizes the approach followed within this deliverable.

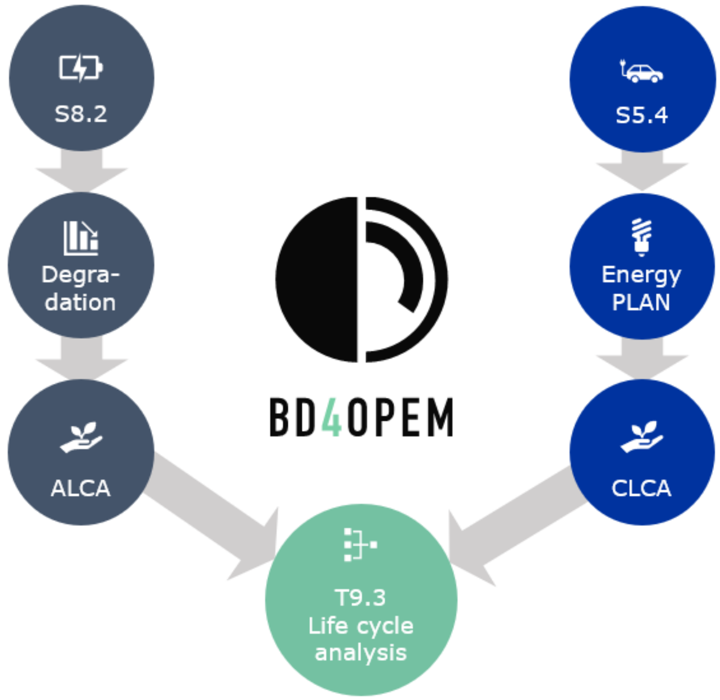

Figure 2: Modelling approach for BD4OPEM T9.3 Life cycle analysis.

3.2 Flexibility and demand response

The service "S5.4 EV to Grid" describes the utilization of EV batteries used as a mobile grid storage, also known as V2G. The rationale behind is that with the decarbonization of the future transportation system, more and more EVs will enter the market. While the capacity of such EVs become bigger and bigger, most of the time, EVs are not used, but remain parked and plugged for charging [23]. With those higher battery capacities, the utilization rate for actual driving becomes lower and lower, leaving those mobile batteries unused. In hand with the decarbonization of the transportation system, more and more fluctuating renewable energy sources (RES) are introduced to the European energy system in order to reach the climate goals of the EU. Due to the intermittent nature of those RES, which production does not automatically correspond to the energy demand, electricity storage is required. Thus, one potential solution to overcome the intermittent production of the RES is to store the electricity production when it is not consumed and supply it at hours of peak or high demand. This is where the unused battery capacities of EV can become handy and help increase the RES penetration of our energy system.

In order to evaluate the environmental impacts of such an energy system, three different scenarios are built to simulate the future energy system in 2050. The scenarios are:

1) CON, representing a conservative scenario,
2) OPT, capturing an optimistic scenario and
3) IDEAL which describes an exaggeration of RES capacities.

Afterwards, different EV charging strategies are introduced in the three scenarios:

1. dump charging, where the EV is immediately after arrival at the destination plugged and charged fully whereas
2. V2G charging is combined with smart charging.

Smart charging refers to a charging strategy that takes into account a minimum state-of-charge of the battery, the peak consumption of the energy system and other influencing factors. Those five scenarios are simulated using the EnergyPLAN software and will be described more in detail in the following chapter.

3.2.1 Energy model and data

To model the energy system, the EnergyPLAN software developed by Sustainable Energy Planning Research Group of Aalborg University is used. EnergyPLAN software simulates the annual operation of any energy system based on flexible demand and supply, taking into account the electricity, transportation and heating vector [24], [25]. Two challenges occurred when defining future scenarios for "S5.4 EV to Grid". First, specific data about future power plants (PPT) or RES capacities, electricity and transportation demands, etc. are not available. International and national policy makers indicate broad ambitions to become climate neutral by 2050, while the path to achieve such goals remain open. Hence, that leaves a lot of room for interpretation. Second, the geographical system boundaries are set to Hovedstaden and Sjælland, which is the second bidding zone of Denmark (DK2). This system boundaries require a finer granulation than country-level data.

The reference year 2022 is modelled consulting Danish national statistics and public available data as following: The energy demand for DK2 is obtained from Energinet while the transportation demand is calculated using statistics on vehicle kilometer per year and region multiplied by the fuel demand per km [26], [27]. The V2G charging is modelled as a combination of smart and V2G charging in EnergyPLAN. In 2022, there is still fossil PPT in place. PPT and RES capacities are obtained from ENTSO-e [28], fuel consumption originates from the Danish Energy Agency [29], while the EV battery capacities are taken from Abdelbaky et al. (2021) [30]. Based on the reference year 2022, three different scenarios are defined: a conservative scenario (CON), a optimistic scenario (OPT) and an ideal scenario (IDEAL). In the conservative scenario, the electricity demand in 2050 is expected to increase by 6%, whereas the transportation demand raises by 4% [31]. Furthermore, the transportation demand in 2050 is assumed to be 80% electric and 20% of alternative fuel demand. Furthermore, the average battery capacity of EVs in the CON are 71 kWh, representing the capacity of small and medium EVs in 2050 [32]. In terms of RES capacities, the CON considers a 2.5 times increase in wind and photovoltaic (PV) installations [33]. Fossil PPT in 2050 are assumed to phase out and retrofitted to biomass PPT. With the uptake of RES capacities however, the previous fossil PPT are expected to decrease by 20% while the biomass PPT will increase by 20%. Additionally, an efficiency improvement up to 39% is considered [34].

Contrary to the conservative scenario, the OPT foresees a 35% decrease of electricity and a 40% decline in transportation demand [31]. The transport demand is expected to be 90% electric while the remaining demand is based on other alternative fuel demand. In the OPT, the average battery capacity is 90 kWh approximating an average of all EV types [32]. The RES capacity for wind and PV in the OPT will raise up to 2.5 times compared to 2022 [29]. The fossil PPT capacity will be reduced by 30% and retrofitted to process biomass, while the current biomass PPT are expected to increase by 50%. At the same time, the PPT efficiency improves up to 50% [34].

The IDEAL is a duplication of the OPT, but with modified PPT and RES production capacities and only V2G charging is introduced to reveal its full potential in a highly renewable energy system. Thus, the 2022 PPT capacities are assumed to both halve by 2050 and only process biomass. The RES capacities in the IDEAL will quadruple by 2050. Relative changes in demand and generation technology capacities are captured in Figure 3, the main parameters describing the different scenarios are summarized in Table 2 and are supported by charts in the annex.

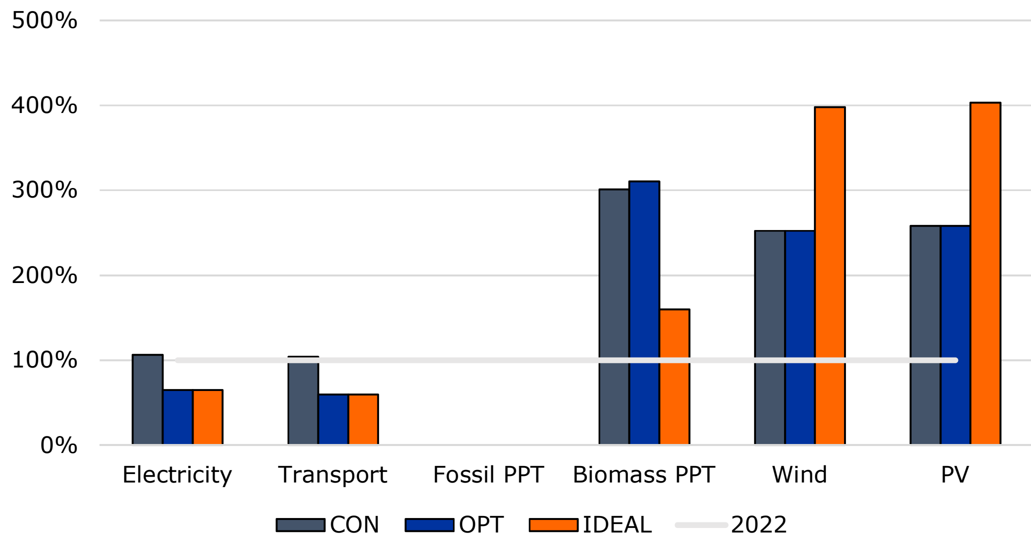

Figure 3: Relative changes in electricity and transport demand and energy generation technologies capacities based on the reference year 2022.

	Unit	2022	CON DUMP	CON V2G	OPT DUMP	OPT V2G	IDEAL V2G
DEMAND							
Electricity demand[1]	TWh	13.05	13.89	13.89	8.48	8.48	8.48
Transport demand[1]	TWh	31.39	32.63	32.63	18.78	18.78	18.78
SUPPLY							
Fossil PPT capacity[2]	MW	2,420	0	0	0	0	0
Biomass PPT capacity[2]	MW	1,063	3,200	3,200	3,300	3,300	1,700
Wind capacity[1]	MW	1,784	4,500	4,500	4,500	4,500	7,100
PV capacity[1]	MW	620	1,600	1,600	1,600	1,600	2,500
EV fleet battery capacity[1]	GWh	3.27	88.38	88.38	50.87	50.87	50.87

Table 2. Overview of parameters to build different energy system scenarios.

3.2.2 Life cycle assessment

To conduct a CLCA, the relevant input and output of processes need to be modeled in a way to represent the changes in the system if the demand is varied. Therefore, the marginal suppliers have to be identified and included. The terminology "marginal suppliers" is used differently in energy science and LCA. While the marginal suppliers of an energy system refers to mix of energy technologies supplying electricity at a certain time, marginal supplier definition in CLCA is slightly different. In CLCA, marginal suppliers are the suppliers responding to an increase in demand as they are the suppliers with the lowest production costs, meaning the most competitive supplier. According to ISO 14049, the marginal, unconstrained supplier is the modern, competitive supplier in case of increasing product demand [35]. As the focus is on electricity at low voltage, an increasing market is assumed (Figure 4).

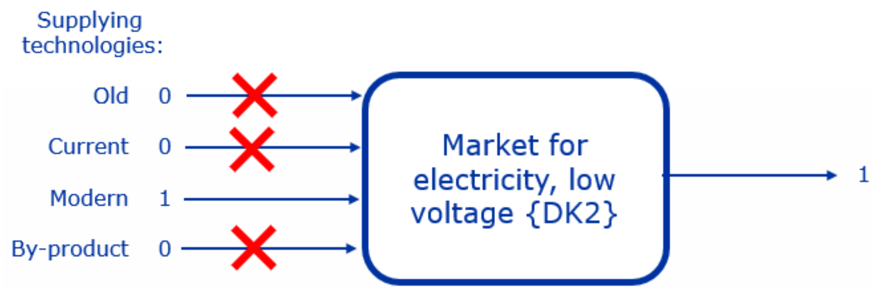

Figure 4: Low voltage electricity market for bidding zone DK2 [35]–[37].

Given the ambition to phase out fossil fuels to become climate neutral by 2050, it is assumed that the fossil PPT are constrained suppliers in 2050 and thus will not be included in the market mix. To identify the marginal long-term electricity mix, it is required to determine the annual growth rate of each scenario, minus the capital replacement rate considering each technology lifetime. The electricity mix of the different scenarios will then include the technologies with a positive, net annual growth rates [35]–[38]. The net annual growth rate of the CON_DUMP is presented in Table 3, while data of the other scenario is available in the annex.

CON_ DUMP	Annual growth 2022-2050	Plant life-time (year)	Capital re-placement	Net annual growth 2022-2050	Classifi-cation	Net annual growth 2022-2050 (GWh/ year)	Long-term marginal mix, incl. import
Gas	-3.6%	30	-3.3%	-0.2%	Old	0.0	0.0%
Wind	5.4%	20	-5.0%	10.4%	Modern	0.6	5.1%
Biomass	45.7%	45	-2.2%	48.0%	Modern	10.2	89.4%
Solar PV	5.6%	30	-3.3%	9.0%	Modern	0.1	0.5%
Import	5775.0%	n.a.	n.a.	5775.0%	n.a.	0.6	5.0%
Total						11.4	100%

Table 3: Compilation of the long-term marginal electricity mix for the CON_DUMP scenario[38].

Next, the ecoinvent database is consulted. ecoinvent is a database containing data on industrial and agricultural processes, taking into account the consumption of natural resources from the environment, related emissions to water, soil and air, consumption of other commodities such as electricity. It covers a large range of sectors on global and regional scale [39]. Ecoinvent is selected due to its great reputation within Europe and its transparency of inventory data. Based on those information, the dataset "market for electricity, high voltage {DK}", "market for electricity, medium voltage {DK}" and "market for electricity, low voltage {DK}" of the consequential ecoinvent database 3.9.1 are modified [36]. First, the supplying technologies are updated based on Table 3, representing the marginal supply mix for the five future modelled supply mixes. Two main modifications of the original datasets of the consequential ecoinvent datasets are undertaken: first, in high voltage market hydro power is removed as this installation is not in the bidding zone DK2. Second, the quantities of each marginal supplier are adjusted according to results of the EnergyPLAN model. The adjustments are visualized in Figure 5.

The modification of the datasets is operationalized using python package Brightway version 2.4.3 [40]. The original ecoinvent datasets for high, medium and low voltage are stored in a new dictionary and the exchanges are updated by the output of the EnergyPLAN model. Consequently, five updated datasets for low voltage level for DK2 are created. Environmental impacts are quantified in terms of climate change (CC), using the Intergovernmental Panel on Climate Change (IPCC) 2013 life cycle impact methodology [41]. Next to CC, the abiotic depletion (AD) for minerals and metals of the life cycle impact assessment method Environmental Footprint version 3.1 is evaluated [42].

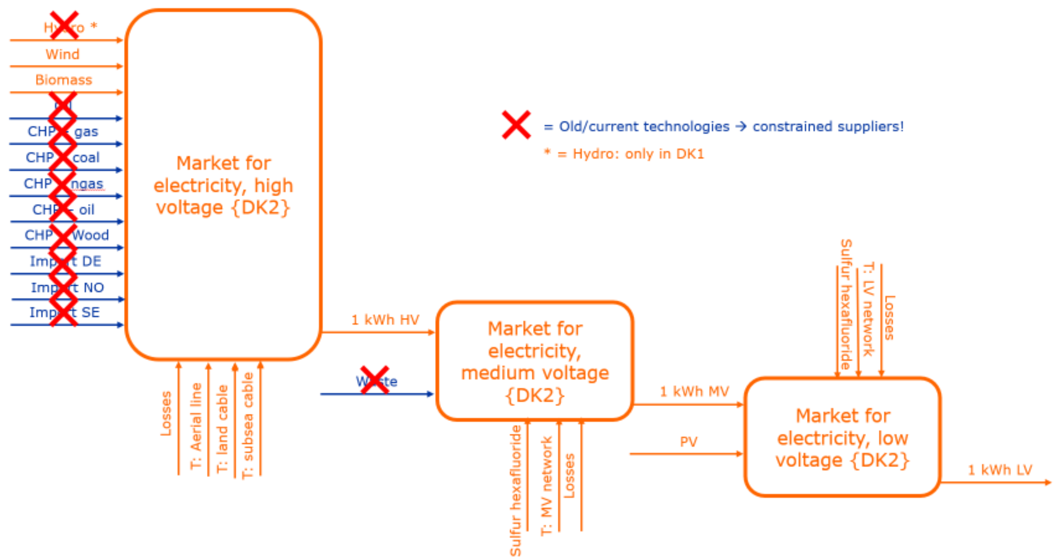

Figure 5: Modification of the "market for electricity {DK2}" dataset.

Figure 5 presents the modified dataset "market for electricity {DK2}. The blue colored activities represent the exchanges included in the cut-off database version, while the orange exchanges represent the exchanges included in the consequential database.

3.3 Asset planning

Capacity fade of energy assets does not result directly in environmental impacts. Environmental impacts of for example renewable energy source technologies occur during their manufacturing, whereas their use stage is considered not to or only minimally contaminate the environment. To still consider the manufacturing impact, such assets are normalized by its production, e.g. CC per kWh produced. Similarly, the environmental impact of degradation can be considered: degradation as of fade in capacity of stationary battery storage does not result in additional environmental impacts. However, if the environmental impacts are normalized by its production output, the degradation will result in a lower production and thus lead to higher impact per production output. Another way to look at degradation is to consider it as consumption. Using the batteries lead to fade in capacity. Consequently, after the lifetime of the battery, the capacity of the battery is reduced and cannot be utilized to the same extent as before the usage. Thus, the cost of the usage can be the impacts linked to manufacturing the lost part of the battery. Degradation itself depends on a variety of factors, such as external temperature, charge- and discharge behavior, depth of discharge, etc. [43]. However, the objective of this deliverable is not to develop degradation models, but quantify the degradation. The environmental impact of degradation is presented in two different ways: first, impact on CC is quantified based on the degradation taking place every timestep. Therefore, data are provided based from BD4OPEM partners and used in an internal developed optimization model similar to the one described in Huber et al. (2023) [44]. Thus, it is assumed that the batteries will have a remaining capacity once they reached 80% of their initial capacity, or they have lost 20% of the initial capacity. This is captured by multiplication of the initial battery energy capacity C_i with the factor 0.2. The CC at each time step in 2019 is calculated using the equation 1.

$$CC_t = \frac{e_m}{(0.2 * C_i)}$$

1: Climate change of battery degradation

where:

CC_t = Hourly CC ($kgCO_2eq$),

e_m = Cradle-to-gate emissions of manufacturing one battery ($kgCO_2eq$) and

C_i = Initial battery energy capacity (kWh).

Second, the CC of the two different batteries are presented per kWh of delivered electricity considering different remaining capacities at their EoL. Considering the different lifetimes of the two batteries, the following remaining capacities at the EoL are assumed:

Remaining capacity compared to initial capacity	Unit	LFP	NMC
Lifetime	Years	19	18
Minimal temperature	% of C_i	68.0	69.7
Average temperature	% of C_i	74.5	76.0
Maximum temperature	% of C_i	82.0	83.0

Table 4: Remaining capacities of two stationary batteries given different temperatures [18], [43].

The extracted factors presented in Table 4 are only used for demonstration purposes in this deliverable and should not be understood as specific data obtained for the project or at the pilot sites. Neither do they represent the same application, hence their correctness can be questioned, but they serve the purpose to exemplify the impact of degradation on a kWh delivered electricity. To present CC per kWh delivered electricity, the cradle-to-gate impacts are calculated using the Intergovernmental Panel on Climate Change (IPCC) CC of 2013 life cycle impact methodology [41]. In a next step, the annually discharged electricity is extracted from a internally developed optimization model and data from a BD4OPEM partner [44]. Hereafter, the lifetime delivered electricity is determined following equation **2**:

$$E_{del} = E_{dis} * F_{deg} * L_n$$

2: Calculation of delivered electricity.

where:

E_{del} = Delivered electricity over lifetime (kWh),

E_{dis} = Discharged electricity in one year (kWh),

F_{deg} = Degradation factor (dimensionless) and

L_n = Lifetime of the battery (years).

As the data obtained represents only one year, it is assumed that the discharged electricity is the same for every year. Additionally, an average degradation factor is applied. This degradation factor is an average of the initial battery capacity and the remaining battery capacity at the batteries EoL (as provided in Table 4). This is a simplification as in reality the battery will degrade differently every year and thus the discharged electricity per year will be different. Thus, the CC per kWh delivered electricity is calculated dividing the CC of the manufacturing of the battery over the lifetime delivered electricity as calculated in equation 2.

3.4 Uncertainty assessment

The presented LCA models are subject to uncertainty and an assessment of the uncertainty linked to the ecoinvent database is covered in this report. In ecoinvent, the quantities reported in each dataset is supported by descriptive statistics such as the lognormal distribution in the ecoinvent database. Lognormal distribution is chosen because the distribution remains greater than zero and does not accidentally use negative values, which in LCA terms would equal giving credits when sampling from this distribution. Limper et al. (2001) provides further explanation on lognormal distributions [45]. The concept of a Monte Carlo analysis is about sampling from the provided distribution. The advantage of Monte Carlo analysis is that the higher the number of samples is, the closer results are approximated. Heijungs (2020) reported, that 1,000 up to 10,000 runs of the Monte Carlo technique are conducted to evaluate uncertainties in LCAs [46]. In particular, this means that one performs the same LCA calculation over and over again using identical models, but each run the calculation uses a different sample within the range of the distribution. When comparing product alternatives, the standard Monte Carlo analysis sampling values from the provided distribution independently. However, this is a limitation as it is not a fair comparison. Instead, the same sampling of the Monte Carlo analysis should be used in order to allow a fair comparison of the product alternatives. Further explanation and a demonstration of a comparative LCA is provided by Henriksson et al. (2015) [47]. Additionally, for the computation of this analysis, the notebook entitled "Comparative Monte Carlo" of Massimo Pizzol is followed [48]. The comparative Monte Carlo analysis is performed only for S5.4 and 10,000 iterations are performed for CC and AD.

4 Results

4.1 Flexibility and demand response

In 2022, around 65% of the produced electricity is generated by fossil PPT, while wind farms produce 25% and PV and biomass PPT account for the remaining electricity. Based on the ambition of the Danish Energy Agency to increase the share of RES up to 2.5 times, wind and PV capacities in the CON_DUMP and CON_S5.4 scenarios roughly account for respectively 41% and 49% of produced electricity. The remaining electricity in those two scenarios is generated by biomass PPTs, accounting for 51% and 59% in the CON_DUMP and CON_S5.4. While the production of RES in the CON is identical, the electricity produced by the biomass PPT increases by 6.9 TWh in 2050, mounting up to a total amount of produced electricity in 2050 of the CON_S5.4 of 38.2 TWh. This is surprising as it occurs in the scenario where the BD4OPEM service is expected to help increase the consumption of electricity produced by the RES. Contrary, the CON where EVs are dump charged, result in overall lower electricity generation (see Figure 6).

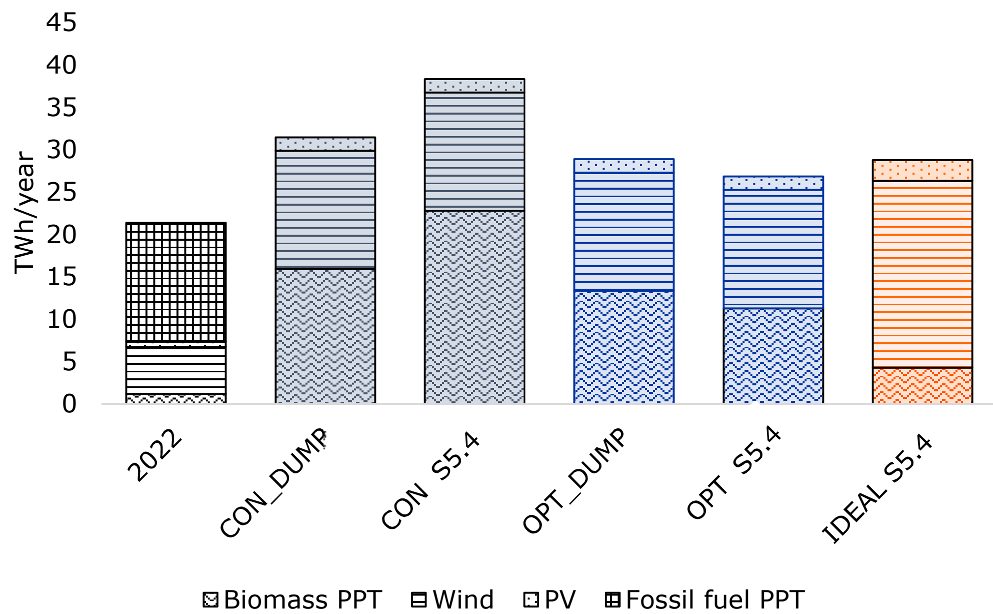

Figure 6: Produced electricity of different energy scenarios for eastern Denmark in 2050.

For the OPT, the scenario where S5.4 is introduced results in overall lower generated electricity compared to the scenario where EVs are dump charged. While the production from wind and PV installations remain equal in both OPT, almost 2 TWh less electricity is produced by the scenario where the BD4OPEM service is introduced. Thus, the share of biomass produced electricity is reduced from 46% in the OPT_DUMP to 42% in the OPT_S5.4. In the IDEAL scenario, around 85% of generated electricity originates from RES, whereas wind produced electricity accounts for 77%. All scenario data are visualized and summarized in the annex.

Another observation is that, while the overall total transport demand varies in 2050, almost the entire transport demand is assumed to be electrified (80% in CON and 90% in OPT). This transport electrification introduces a high interlinkage between the electricity and the transport sector. While this approach is perceived to reduce the CC of the transport sector in combination with an electricity sector mainly based on RES, it also poses challenges on the electricity sector to be capable of supplying all the demand. Apart from analyzing the long-term marginal electricity supply, the different EV charging strategies can be evaluated in terms of the independence of the different energy scenarios and the amount of curtailed excess electricity can be evaluated. Limiting both the imports and production of excess electricity ensures political independence and a good utilization of resources. Considering this, the benefit of the S5.4 service become visible: In the scenarios where the service is introduced, the share of produced electricity rises. In the CON scenario, the system generated electricity doubles from around 40% up to more than 80%. At the same time, introducing the S5.4 service avoids the production of excess electricity or reduces it to a neglectable amount. A similar trend can be observed for imported electricity: from accounting almost for 50% of utilized electricity in the CON_DUMP scenario, the service S5.4 helps to limit the import to below 20%. Thus, in the CON scenario where the service is introduced the share of the system produced electricity rises up to 80%. In the OPT scenario, the share of the system generated electricity is much higher, almost at 80%. Introducing the S5.4 service in this scenario helps to mitigate curtailed electricity completely and keep imports low. In the IDEAL scenario, the combination of much higher RES penetration and lower production of biomass electricity results in a lower share of system generated electricity, requiring still import and leaving some electricity to curtail.

In terms of CC, the CON_S5.4 scenario has the highest CC linked to the increase biomass production. In the OPT scenario, the scenario where S5.4 is introduced shows less CC than in the same system with dump charging only. The CC is not directly influenced by the service S5.4. Improved CC is observed in systems where higher wind and PV penetration is found. As providing service S5.4 in the scenarios help to increase the wind and PV consumption in those systems, it also presents lower CC compared to a system where this service is not provided (Figure 7).

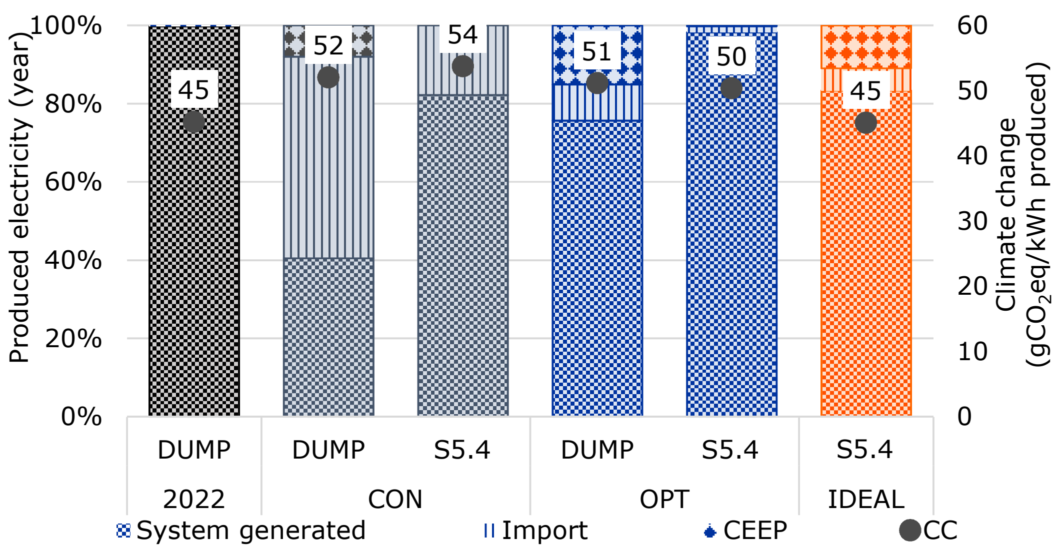

Figure 7: Overview of energy system independency of different energy scenarios for eastern Denmark when introducing dump charging and BD4OPEM service S5.4.

Figure 8 presents the transport demand of the three scenarios where service S5.4 is provided. Due to charge-discharge efficiency, the supply of electricity is higher than the actual demand. Due to the constraint that dump charging makes up only 5% of

EV charging, the demand for dump charging is almost neglectable. Considering the supply side of the EVs shows that almost all electricity is used to charge the EVs. Electricity supply from EVs back to the grid only occurs to a maximum of 2% in the IDEAL scenario, whereas in the other two scenarios, hardly any electricity is fed back to the grid. Contrary, if the services are introduced in the different energy scenarios, an increased share of system generated electricity and a reduced CC is observed. Thus, even though the amount of discharged electricity from EVs back to the grid is rather limited, there are benefits in terms of energy independence and increase wind and PV integration.

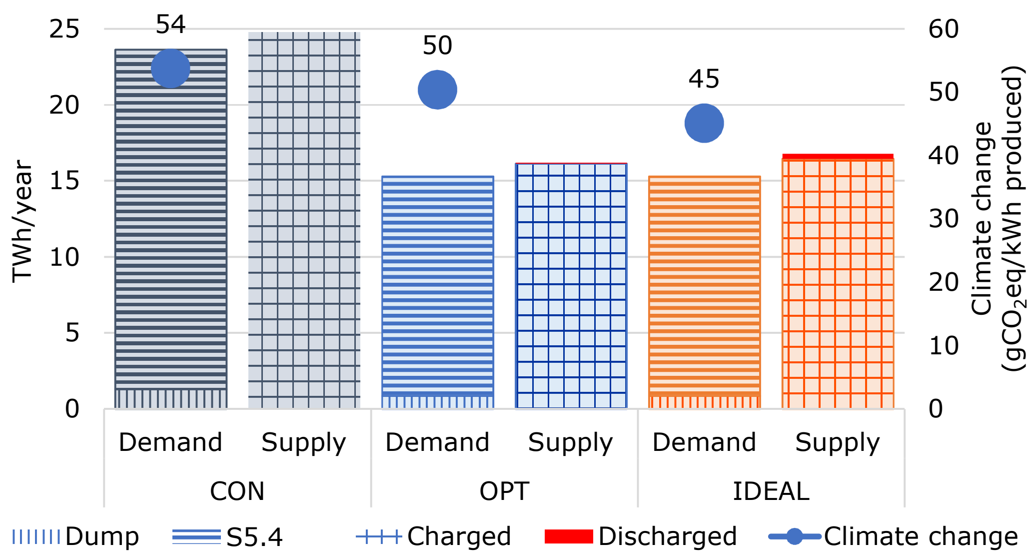

Figure 8: Transport electricity flows in the BD4OPEM service S5.4.

As described before, CC is declining in the scenarios where more wind and PV installations are contracted and S5.4 helps integrating those RES sources. Contrary to CC, AD increases with the rise of higher wind and PV capacities. For example, highest AD is found in the scenarios where most electricity is generated by biomass PPT (see Figure 9). The impact category AD was used here to highlight, that even though CC can be reduced by introducing energy services such as S5.4, its introduction might actually stress other impact categories, such as AD. However, a detailed evaluation is not conducted within this deliverable and remains subject to further research.

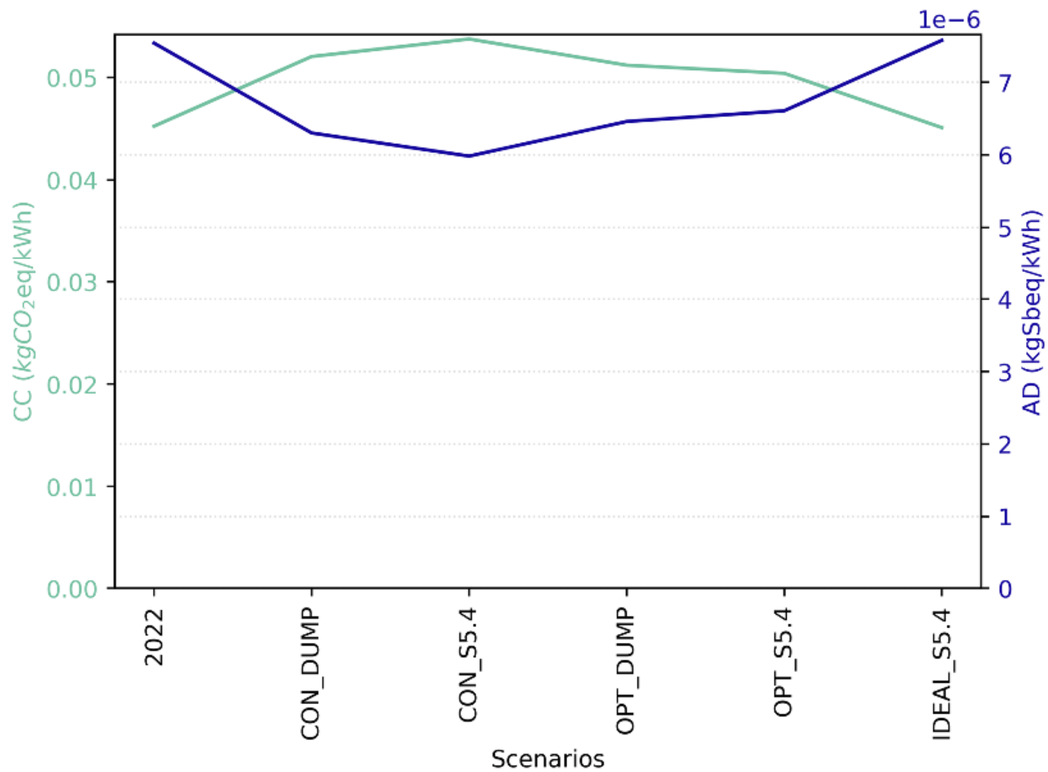

Figure 9: CC and AD of different energy scenarios for eastern Denmark in 2050.

4.2 Asset planning

The cradle-to-gate CC of the LFP and the NMC is 43,839 and 116,744 kg CO_2eq over their lifetime. Those emissions are then distributed over the degradation occurring at each single time step. Due to higher cradle-to-gate CC, the CC per timestep is higher for the NMC compared to the NMC (see left two subplots of Figure 10). The variation of the CC degradation for both batteries is identical as the same simulation output is used to calculate the CC per timestep. Another observation can be made: The right sublot of Figure 10 presents the cradle-to-grave CC of the two batteries, while the CC degradation is presented only for one year. When comparing the CC degradation to the total cradle-to-gate impact of the two batteries, the CC of the degradation becomes hardly visible as its magnitude is smaller.

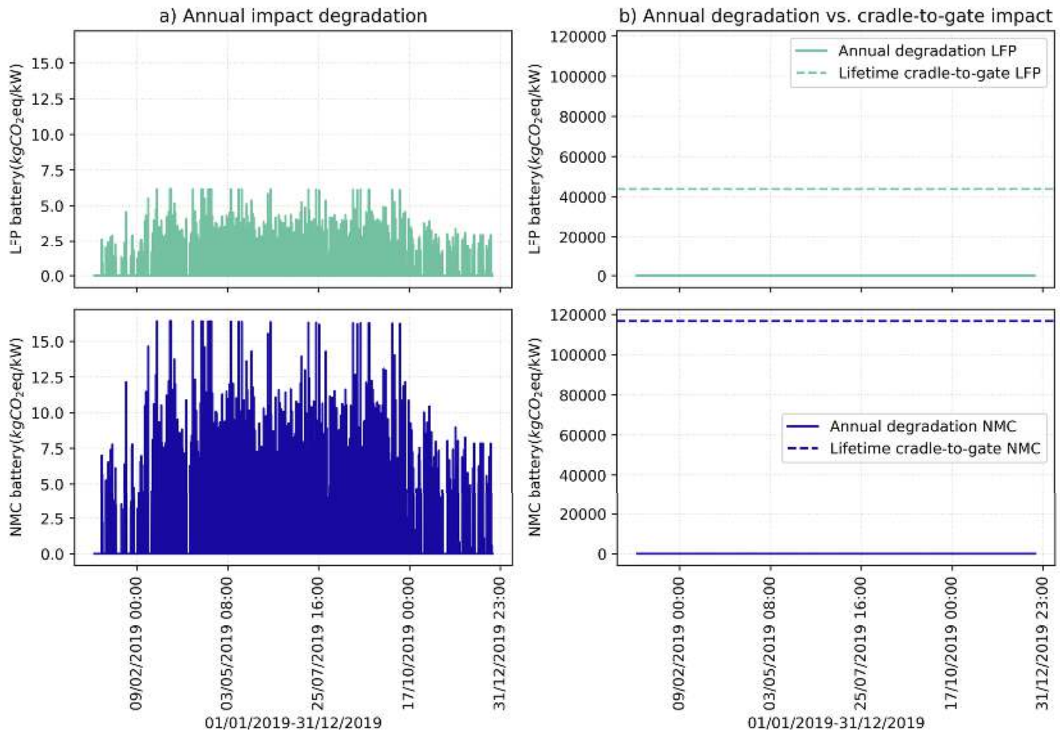

Figure 10: CC impact of stationary battery degradation as calculated by service S8.2.

Besides quantification of degradation in environmental impacts, this section describes the indirect impact of degradation. Due to degradation, the batteries are not capable of supplying the same amount of electricity as at the beginning of their lives. Thus, introducing degradation to determine the lifetime supplied electricity, less delivered electricity can be supplied. As a consequence, the CC per kWh delivered electricity is increasing. Again, due to higher CC of the manufacturing, the CC for NMC is higher than for LFP. Applying the degradation factors provided by Gräf et al. (2022), Figure 11 shows an increase in CC per kWh delivered with lower remaining battery capacity at the EoL [43].

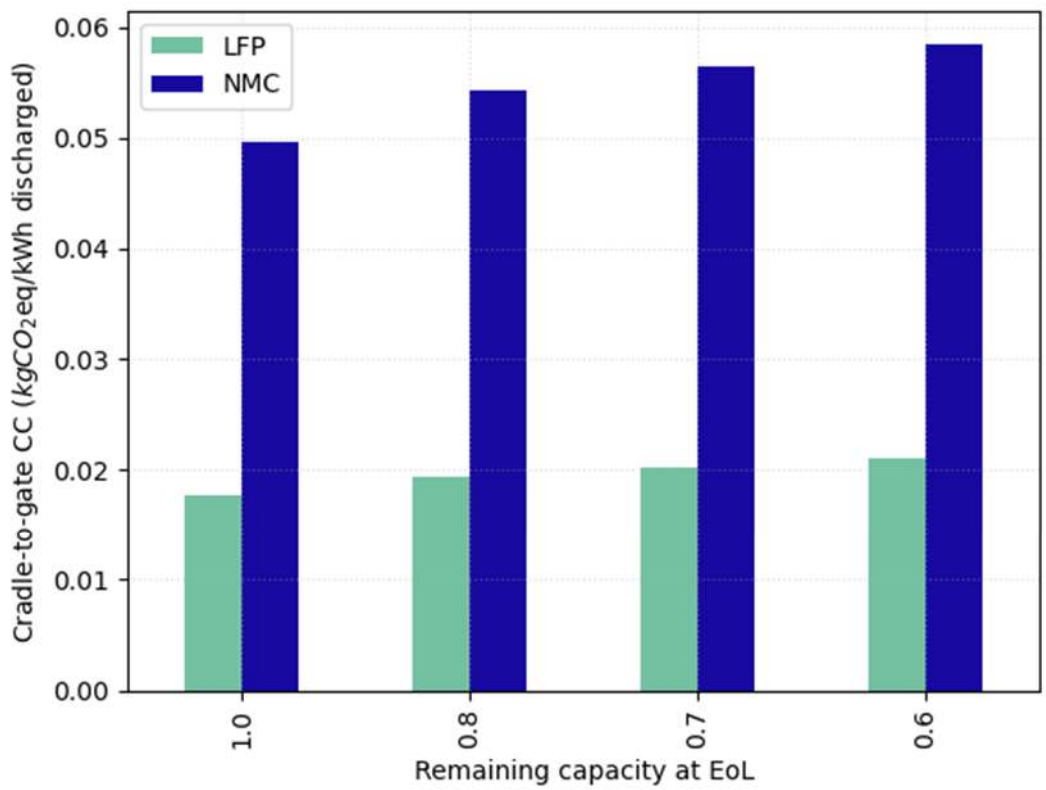

Figure 11: Climate change impact of two stationary batteries assuming different remaining capacities at the batteries life end as indicated by Table 4.

As provided by this analysis, quantifying the degradation in terms of environmental impacts does not reveal highly novel results. Interesting from an environmental perspective however might be if due to asset degradation, more or bigger installations would be commissioned. Increased consumption always comes along with an environmental cost. To identify such impacts, an improved asset sizing and optimization model considering degradation mechanism is required. Challenging at this stage is still the quantification of degradation itself. Thus, both the development of further asset degradation models and their integration into more advanced modelling software remains subject for further research.

4.3 Uncertainty evaluation

While Table 5 presents the CC and AD of all scenarios, Figure 12 and Figure 13 visualize the stochastic results based on the comparative Monte Carlo analysis. For CC, the same tendencies can be observed for both approaches: the CON scenario with S5.4 reveals highest impacts while least CC is emitted in the IDEAL scenario. Additionally, the CON scenario with S5.4 presents the highest spread of CC amongst all scenarios. Thus, it can be concluded, that considering the uncertainty linked with the ecoinvent database, still the IDEAL scenario has lowest CC. When comparing the arithmetic mean of the CC obtained from the Monte Carlo analysis to the CC obtained by the standard LCA shows that the comparative Monte Carlo results are higher.

Energy scenarios DK2	CC	CC_CMC	AD	AD_CMC
Units	gCO_2-eq/kWh	gCO_2-eq/kWh	kgSb-eq/kWh	kgSb-eq/kWh
DK2022	45.24	57.06	7.54e-06	3.33e-06
CON_DUMP	52.03	71.53	6.30e-06	2.59e-06
CON_S5.4	53.73	75.48	5.98e-06	2.40e-06
OPT_DUMP	51.18	69.55	6.45e-06	2.68e-06
OPT_S5.4	50.39	67.82	6.61e-06	2.77e-06
IDEAL_S5.4	45.10	56.80	7.58e-06	3.35e-06

Table 5: Climate change and mineral and metal abiotic depletion for different energy scenarios in easter Denmark in 2050.

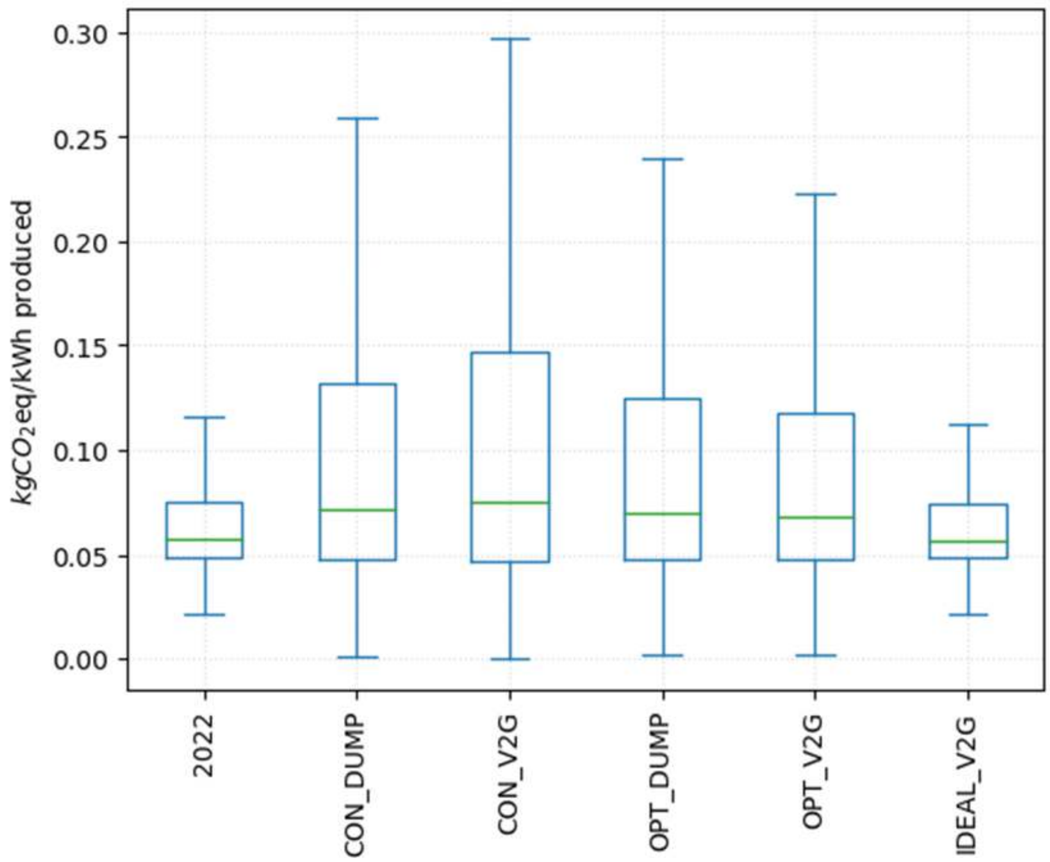

Figure 12: Climate change results of the comparative Monte-Carlo analysis of the different energy scenarios for eastern Denmark in 2022.

Similar to CC, the both AD results complied with a standard LCA and a comparative Monte-Carlo analysis underline the same conclusion: the scenario with higher biomass PPT capacities are found to use least mineral and metal resources. Contrary, the 2022 and the IDEAL scenario where the service S5.4 is introduced result in highest mineral and metal use. Comparing the arithmetic mean values obtained from the comparative Monte-Carlo analysis with the standard LCA shows slightly higher AD impact for the comparative Monte-Carlo results. On the other hand, the spread of the comparative Monte-Carlo analysis is over all scenarios a similar (Figure 13).

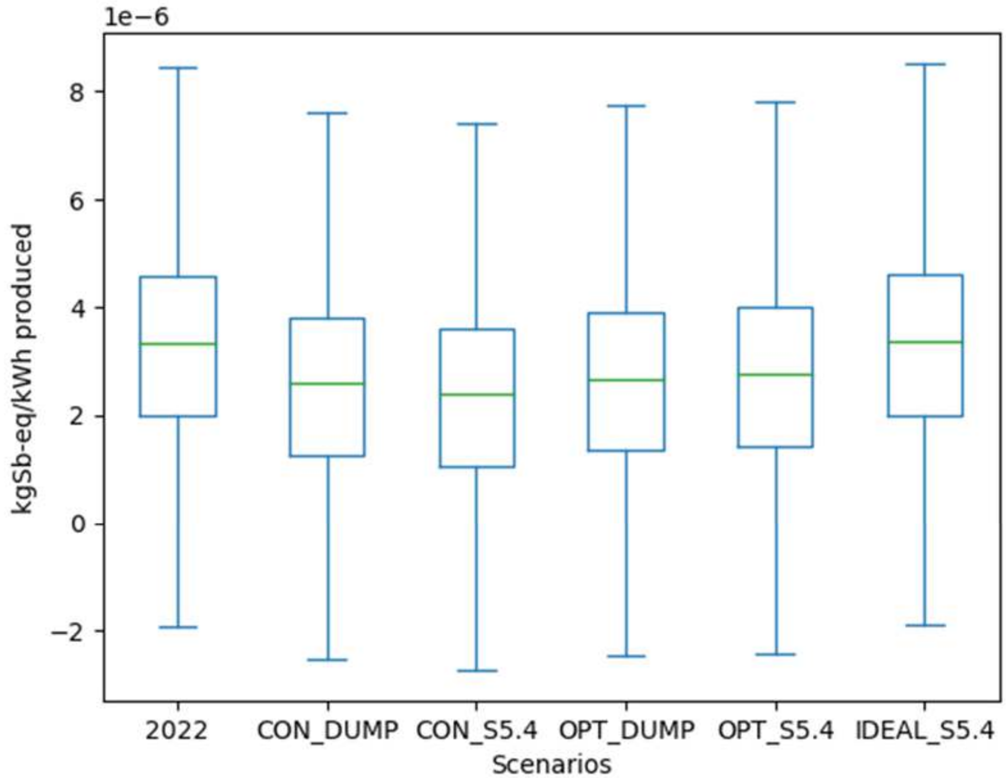

Figure 13: Mineral and metal abiotic depletion results of the comparative Monte-Carlo analysis of the different energy scenarios for eastern Denmark in 2022.

This is a strong indication, that the obtained results performing a standard LCA should not be used as an exact/certain indication, but it could potentially highlight towards a tendency which energy scenario would be more beneficial when running S5.4. Furthermore, none of the Monte Carlo results identified one scenario to be superior in terms of environmental impacts than others. Thus, either the uncertainty of the database hinders identifying a scenario outperforming all others or it shows that the charging strategies, e.g. introducing S5.4 does not help reducing CC compared to a system in which those services are not introduced. Additionally, the spread of CC results in the Monte Carlo for the reference year 2022 and the IDEAL scenario is smaller than for the other scenarios. As all scenarios are built using the same exchanges, an open question remains where the lower ranges in the two scenarios originates from. It is observed that in the reference year 2022 and the IDEAL scenarios more biomass is used. However, this remains to be further investigated in further research.

5 Interpretation and discussion

Results are computed for introducing the V2G services as described in the BD4OPEM service S5.4. Therefore, a CLCA is conducted and inputs are obtained from an energy modelling tool. When interpreting the CC obtained from CLCA, it is important to have in mind that those impacts represent the changes in the energy system and do not account for the entire energy system itself. Consequently, the computed CC captures the environmental impact of increasing the electricity demand by one kilowatt-hour. When compiling CC and AP, the results are found to be in similar magnitude, revealing different scenarios to be beneficial. When carrying out the comparative Monte Carlo simulations, the impacts of the single scenarios approximated even more, hampering the identification of a single, most advantageous scenario. As a next step, the uncertainty in the background data can be further evaluated. Additionally, a global sensitivity to investigate further on the uncertainty linked to the foreground mode could be added. An ongoing point of discussion and research focus in LCA is the robustness of impact categories in the future.

Besides the limitations on the CLCA, some limitations of the energy model also exists. First, the purpose of building this energy model is not to determine or outline exactly different energy scenarios for eastern Denmark. Instead, the energy models are built to understand the impacts of different EV charging strategies and the related environmental impacts. Another point to mention is the role of biomass in the future Danish electricity mix. Following the CLCA approach, constrained suppliers cannot be marginal suppliers. In this analysis, the limitation of biomass sources for the Danish energy system has not been reflected. If however in a future Danish energy system the biomass resources have been fully exploited, biomass will not act as a marginal supplier in the electricity mix.

In addition, the marginal suppliers are identified assuming an increasing market trend, as given in the CON scenario, but for the OPT and IDEAL scenario, a decreasing market trend is given. Thus, the marginal suppliers in such a case should be the least competitive ones. The marginal suppliers are defined similarly for all scenarios neglecting the market growth potential.

The results show some unexpected outcomes: A maximum of 2% electricity charged in the EVs is fed back into the grid. This appears surprising as on an individual EV level, the V2G services are observed to be higher [49]. The difference between the discharged electricity from EVs on a large-scale versus an individual vehicle level remains open for future investigations. Linked to this observation is also the question about implications for the LCA.

With respect to the assessment of service 8.2, the insights obtained from LCA results proved to be limited. While integrating precise degradation models of different assets might help to enhance energy optimization models, no new insights are obtained by assessing those degradation models isolated and on an individual asset level. However, conducting an LCA for an energy system incorporating such degradation models can help to make those evaluations more precise.

Next to limitations regarding applied methodology, the setup of the environmental analysis in this context can be reflected. If the target is to evaluate single services, the services have to be demonstrated at certain locations in order to get the required data. At the current stage of the developed market platform, this is, however, not yet possible. On the contrary, the LCA can also be conducted for the service platform itself, e.g. taking into account the required IT infrastructure such as data centers, computers, cables, cloud storage etc. and the energy consumption. The environmental impact of the IT infrastructure and the energy consumption on an individual service level might be negligible. However, there are also other studies highlighting in particular the high energy consumption of the servers during their use stages and the associated environmental impacts [50], [51]. Thus, in future studies, the focus could, instead of evaluating the environmental impacts on a service level, be to investigate further into the IT infrastructure on a larger scale, e.g. what are the environmental impacts of the IT infrastructure and the energy consumption if those services would be run, e.g. all over Europe.

6 Conclusions

This study present an LCA conducted in the context of the BD4OPEM project. Two services of the developed BD4OPEM market platform are selected and evaluated applying a LCA methodology. Service S5.4 describes the introduction of V2G services of individual EVs to the national grid. In order to evaluate this service, the energy modelling software EnergyPLAN is applied to eastern Denmark and the output is used to identify the marginal suppliers for the consequential CLCA. To the author's knowledge, an identical study has not been conducted yet. To show the CC and AP of introducing service S5.4, next to the reference year 2022, three different scenarios are defined for 2050: 1) a conservative scenario (CON), 2) an optimistic scenario (OPT) and 3) an ideal scenario (IDEAL). Differences in energy technology capacities, demands and EV battery capacities are used to distinguish the scenarios. Next, two different EV charging strategies are introduced in each of the scenario: 1) Dump charging and 2) Service S5.4. Obtained results are then used to modify the low voltage market dataset for Denmark from the consequential database of ecoinvent version 3.9.1. To assess the uncertainty of the background database, a Monte Carlo analysis with 10,000 runs is performed for both compilation of CC and AP. Next to the service S5.4, the service S8.2 "Asset estimation optimization for microgrids" is assessed applying an attributional LCA. In particular, the developed degradation models are included in the LCA of two stationary batteries, namely an LFP and a NMC battery. The hourly, environmental cost of degradation is then computed based on the cradle-to-gate environmental impacts of the two batteries and the degradation at each time step. Alternatively, the CC per battery capacity is updated considering the degradation of the battery and the associated lower lifetime discharged electricity.

In 2050, the wind electricity will increase considerably and account from 36% in the CON_S5.4 scenario up to 77% of generated electricity in the IDEAL scenario. While PV installations generates a minor part of electricity, the remaining electricity is sourced from biomass power plants. Furthermore, the electricity fed back from the EVs to the grid is found to be 2% of the charged electricity for the EVs. In terms of environmental impacts, the highest CC, namely 54 g CO_2eq/kWh generated is calculated for the CON_S5.4 scenario, whereas lowest, in particular 45 g CO_2eq/kWh is found at the IDEAL scenario, which represents an exaggerated shared of wind energy in combination with the developed BD4OPEM service. Contrary to CC, the lowest AP is calculated for the CON_S5.4 and highest AP occurs in the IDEAL scenario. On the other hand, the results of the Monte Carlo simulation do not allow to identify one scenario as superior neither for CC nor for AP. Given this observation, it remains open whether one of the scenarios can be identified as more beneficial than others or if the similarity in result is simply due to a too high uncertainty in the background database. Including the degradation models of the batteries into the environmental assessment results in higher CC impact. The impacts increase for an LFP battery from 18 g CO2eq/kWh battery capacity at the beginning of its lifetime up to 21 g CO2eq/kWh battery capacity considering a remaining battery capacity at the EoL of 68%.Compared to the cradle-to-grave impact, the hourly CC of degradation remains for both stationary batteries low.

Despite its efforts, this deliverable is subject to some limitations and specific modelling choices. First, biomass is assumed to be an unconstrained supplier, neglecting the natural constrains of available biomass in Denmark. Second, future scenarios are built assuming an in- or decrease of transportation and electricity demands. In- and decreasing demands however implies modelling constrained suppliers differently. Only increasing market trends are considered for the CLCA. Third, the uncertainty in the foreground system remains unknown. Finally, the environmental evaluation of service S8.2 allows limited insights, claiming for a more systematic approach to fully uncover the impacts associated with that service.

This work presents an environmental assessment of two services obtained from a market platform. Future work can target to understand better the impact of uncertainty in the background database and the specific processes accounting for it. Contrary to the systematic perspective to assess service S5.4, research efforts could focus on understanding the environmental impact on individual asset level and the interrelation between this micro and macro perspective. With respect to S8.2, a more systematic approach is required to conceptualize the environmental impact of the asset optimization models. Finally, next to the assessment of individual services, also the evaluation of the IT infrastructure, the data processing and storing could be subject of future research.

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Annex

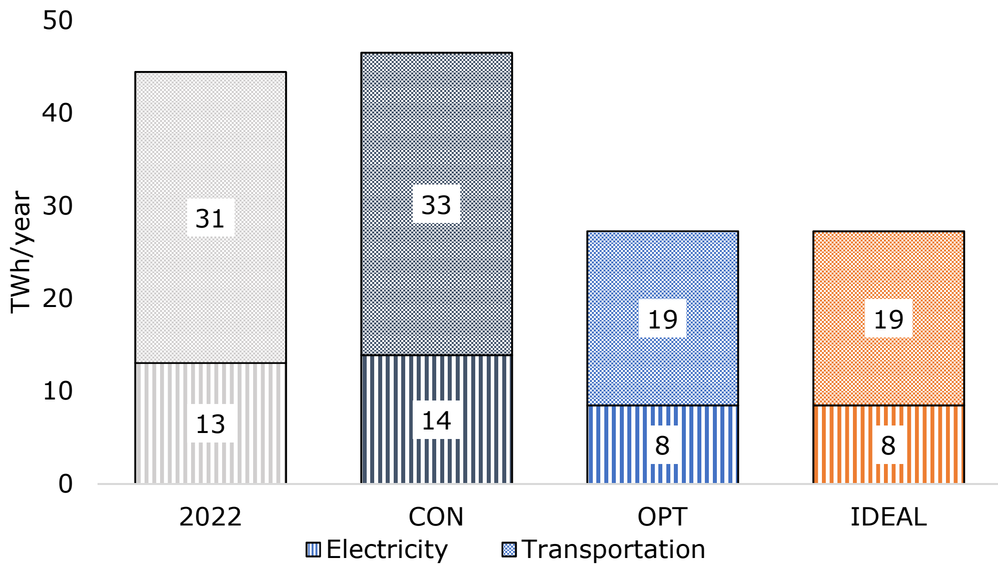

Figure 14: Energy demand of different energy scenarios for eastern Denmark in 2050.

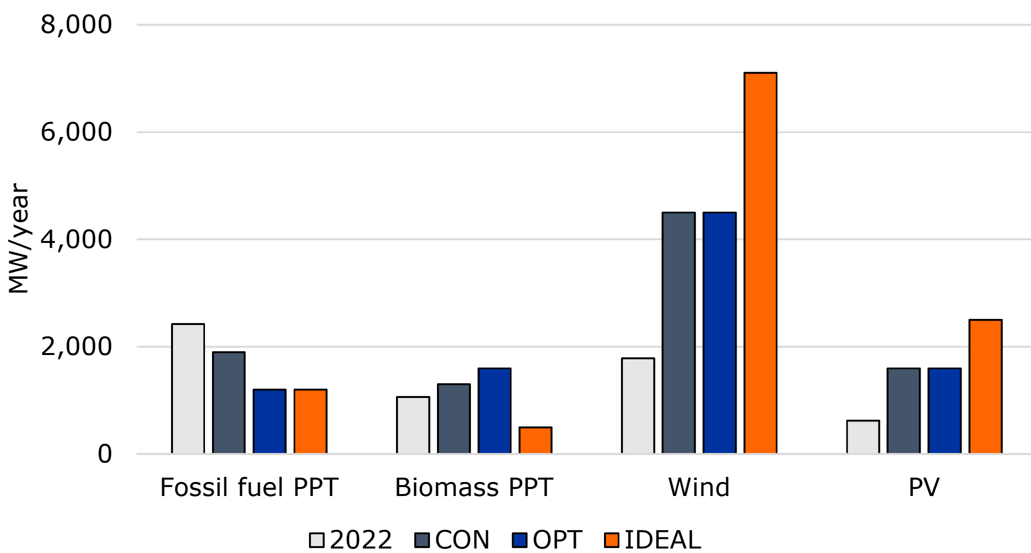

Figure 15: Capacities of different energy scenarios for eastern Denmark in 2050.

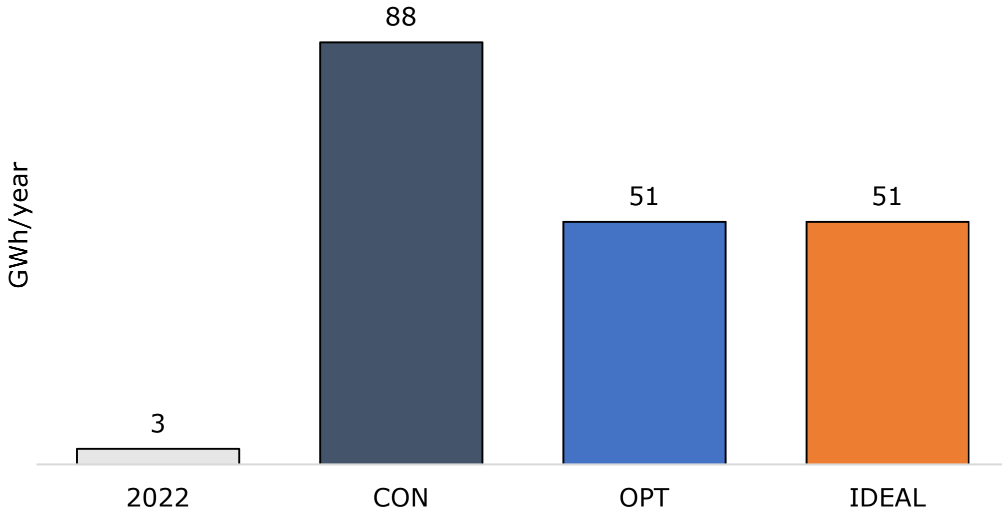

Figure 16: EV fleet battery capacities of different energy scenarios for DK2 in 2050.

	2022	CON DUMP	Diff	CON V2G	Diff	OPT DUMP	Diff	OPT V2G	Diff	IDEAL V2G	Diff
Domestic production (P)											
NG	14.0	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	-0.5	0.0	-0.5
Biomass	1.2	15.9	0.5	22.8	0.8	13.3	0.4	11.3	0.4	4.3	0.1
Solar	0.6	1.6	0.0	1.6	0.0	1.6	0.0	1.6	0.0	2.5	0.1
Wind	5.5	14.0	0.3	14.0	0.3	14.0	0.3	14.0	0.3	22.0	0.6
Total	21.3	31.4		38.3		28.9		26.8		28.7	
Import (I)											
Import	0.0	16.2	0.6	6.8	0.2	2.7	0.1	0.4	0.0	1.6	0.1
P & I	21.4	47.6		45.1		31.5		27.2		30.4	

Table 6: Data of energy production and imports in eastern Denmark in 2022 and 2050.

CON_ V2G	Annual growth 2022-2050	Plant lifetime (years)	Capital replace-ment	Net annual growth 2022-2050	Classifi-cation	Net annual growth 2022-2050 (GWh/ year)	Long-term marginal mix, incl. import
Gas	-3.6%	30	-3.3%	-0.2%	Old	0.0	0.0%
Wind	5.4%	20	-5.0%	10.4%	Modern	0.6	34.6%
Biomass	67.1%	45	-2.2%	69.3%	Modern	0.8	47.7%
Solar PV	5.6%	30	-3.3%	9.0%	Modern	0.1	3.3%
Import	2428.6%	n.a.	n.a.	2428.6%	n.a.	0.2	14.5%
Total						1.7	100.0%

Table 7: Compilation of the long-term marginal electricity mix for the CON_V2G scenario.

OPT_ DUMP	Annual growth 2022-2050	Plant life-time (year)	Capital replace-ment	Net annual growth 2022-2050	Classifi-cation	Net annual growth 2022-2050 (GWh/ year)	Long-term marginal mix, incl.. import
Gas	-3.6%	30	-3.3%	-0.2%	Old	0.0%	0.0%
Wind	5.4%	20	-5.0%	10.4%	Modern	57.8%	34.6%
Biomass	37.8%	45	-2.2%	40.0%	Modern	46.0%	27.5%
Solar PV	5.6%	30	-3.3%	9.0%	Modern	5.5%	3.3%
Import	942.9%	n.a.	n.a.	942.9%	n.a.	9.4%	5.6%
Total						118.7%	71.0%

Table 8: Compilation of the long-term marginal electricity mix for the OPT_DUMP.

OPT_ V2G	Annual growth 2022-2050	Plant life-time (year)	Capital replace-ment	Net annual growth 2022-2050	Classifi-cation	Net annual growth 2022-2050 (GWh/ year)	Long-term marginal mix, incl. import
Gas	-3.6%	30	-3.3%	-0.2%	Old	0.0	0.0%
Wind	5.4%	20	-5.0%	10.4%	Modern	0.6	55.9%
Biomass	31.4%	45	-2.2%	33.6%	Modern	0.4	37.4%
Solar PV	5.6%	30	-3.3%	9.0%	Modern	0.1	5.3%
Import	146.4%	n.a.	n.a.	146.4%	n.a.	0.0	1.4%
Total						1.0	100.0%

Table 9: Compilation of the long-term marginal electricity mix for the OPT_V2G scenario.

IDEAL_ V2G	Annual growth 2022-2050	Plant life-time (year)	Capital replace-ment	Net annual growth 2022-2050	Classifi-cation	Net annual growth 2022-2050 (GWh/ year)	Long-term marginal mix, incl. import
Gas	-3.6%	30	-3.3%	-0.2%	Old	0.0	0.0%
Wind	10.6%	20	-5.0%	15.6%	Modern	0.9	75.6%
Biomass	9.6%	45	-2.2%	11.8%	Modern	0.1	11.9%
Solar PV	10.8%	30	-3.3%	14.1%	Modern	0.1	7.5%
Import	578.6%	n.a.	n.a.	578.6%	n.a.	0.1	5.0%
Total						1.1	100.0%

Table 10: Compilation of the long-term marginal electricity mix for the IDEAL_V2G scenario.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 872525