Economic, Environmental, Societal and Technological Impact Factors in the Transition of the German Energy System – Investigations from a Prosumer's Perspective

Von der Fakultät für Wirtschaftswissenschaften der
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vorgelegt von

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Summary

The German energy transition is a major challenge that requires the efforts of many different actors. In the energy market, key factors for this change are the finite nature of fossil fuels and, above all, the need to counteract the progress of anthropological climate change. Therefore, the generation of electricity, the essential commodity, is currently being converted from a centralised structure based on fossil fuels and nuclear energy to a decentralised one based on renewable energies.

This transition is not voluntary, but is driven by regulations and subsidies, and the form that they take depends on political decisions. Therefore, this dissertation first studies the interaction of the various impact factors in the process of the energy transition. In addition, the example of the private prosumer is used to examine how the regulations and subsidies affect the individual actor: which measures are successful, and where is a need for action in order to achieve the set goals.

This dissertation consists of two parts. The first part presents a comprehensive overview of the work. It outlines the topic and motivation, the underlying theoretical constructs, the methodologies used as well as the key findings of the included research papers and the conclusion.

The second part covers the four research papers underlying this dissertation.

Research Paper 1 identifies economic, ecological, societal and technological impact factors of the German energy transition and examines their interactions. For this purpose, the methodology of cause-and-effect analysis is used. The paper also analyses how the regulatory and market environment for established energy producers has changed over time. It is shown that the process of the energy transition has built up over a long period of time and has been driven from the beginning by social processes, which have resulted in political measures and regulations that are supported by individual environmental events.

Research Paper 2 examines from a financial perspective the private prosumer who is operating a photovoltaic system and a battery storage system under German market conditions. Using the concept of total cost of ownership, a comprehensive model is developed that maps all relevant cash flows over the entire life cycle from the prosumer's perspective, taking into account all regulations. Using real-world data, different constellations of the private prosumer are evaluated and compared with each other with regard to their advantageousness. The results obtained are unambiguous. Regardless of the household size, the operation of the largest

possible PV system is always financially advantageous for the private prosumer. Battery storage solutions, however, have the opposite outcome, which means that they are not profitable to a prosumer in any configuration. Even though a battery storage system has a clearly positive effect on the self-sufficiency rate and ensures savings in operation, this effect does not outweigh the high investment costs.

By applying the concept of sector coupling, Research Paper 3 continues the previous investigations. The heat sector is represented by the use of a heat pump in comparison with a gas heating system and a heating rod. The transport sector is represented by the private charging of an electric car. In addition to the financial evaluations based on an extended model, again using the concept of total cost of ownership, the study considers the resulting greenhouse gas emissions during the use phase. Operating a battery storage system does not become financially advantageous via the approaches examined with sector coupling. From a purely financial perspective, the use of a heat pump does not show any benefits compared to gas heating. The reasons for this include the high investment costs. Regarding the self-sufficiency rate and the self-consumption rate, clear advantages can be identified which also have a positive effect on greenhouse gas emissions. A decrease in investment costs and a possible increase in CO_2 taxation can lead to a change in the advantages.

Research Paper 4 examines the environmental performance of the private prosumer using the methodology of life cycle assessment. The prosumer's assets and electricity flows are mapped and evaluated with regard to different impact categories. Results of previous studies on single assets and an environmental database are used to assess the prosumer as a whole in terms of that household’s environmental impacts for the first time. In terms of greenhouse gas emissions, the effects of photovoltaics and battery storage can be assessed as consistently positive. However, these advantages are counterbalanced by disadvantages in other impact categories, especially in the domain of battery storage.

In summary, this dissertation shows the relationships between the various impact factors in the German energy transition and their interactions by using the example of the private prosumer. From a scientific perspective, the thesis provides a detailed financial and environmental assessment and gives implications for both private decision-makers and regulators.

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List of Abbreviations

€	Euro
BES	Battery Energy Storage
BEV	Battery Electric Vehicle
CAPEX	Capital Expenditure
CO_2	Carbon Dioxide
CSR	Corporate Social Responsibility
DC	Direct Current
DSO	Distribution System Operator
EBIT	Earnings Before Interests and Taxes
EEG	Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz)
EoL	End-of-Life
EPT	Energy Payback Time
EU	European Union
FNA	Federal Network Agency (Bundesnetzagentur)
FU	Functional Unit
GHG	Greenhouse Gas
GW	Gigawatt
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change
KfW	Kreditanstalt für Wiederaufbar
kWh	Kilowatt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LNG	Liquid Natural Gas
MW	Megawatt
NGO	Non-Governmental Organisation
NPP	Nuclear Power Plant
NPV	Net Present Value

ODP	Ozone Depletion Potential
OPEX	Operational Expenditure
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
RES	Renewable Energy Sources
RP	Research Paper
TAP	Terrestrial Acidification Potential
TCO	Total Cost of Ownership
TCO_P	Prosumer-Oriented Total Cost of Ownership
UN	United Nations
VAT	Value Added Tax
VBA	Visual Basics for Applications

Part 1: Comprehensive Overview of the Dissertation

The present dissertation is composed of two parts. Part 1 is a comprehensive overview of the dissertation. Part 2 consists of four papers which analyse the underlying research questions.

The structure of the present cumulative dissertation is shown in the following figure:

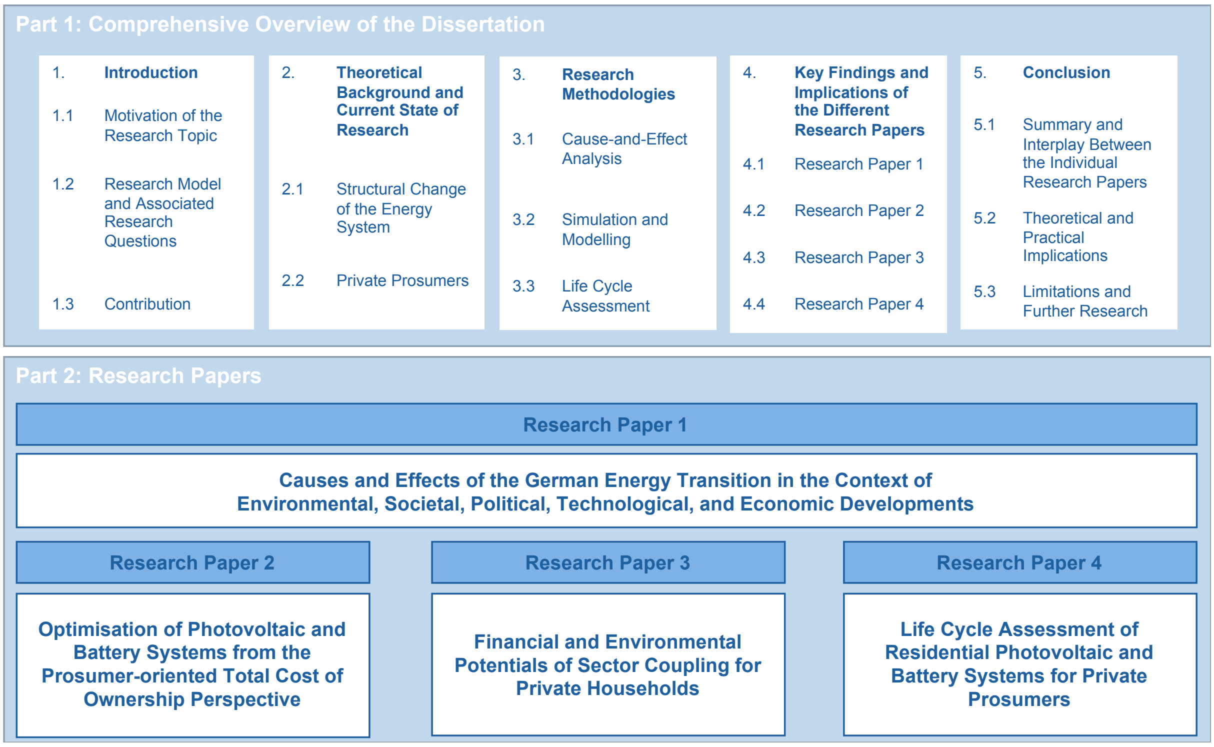

Figure 1: Structure of Dissertation

Part 1 provides a comprehensive overview of the contents of this dissertation. First, the underlying research topic is introduced. To this end, the topic is motivated and the developed research model together with the associated research questions is presented. The contributions of the research papers included in this dissertation are presented. Following, the theoretical background and the current state of research are elaborated. The next chapter contains the research methods used in this dissertation. Furthermore, the core elements of the four research papers included in this dissertation are explained. The final chapter, the conclusion, collects the findings of the individual research papers, including theoretical and practical implications as well as limitations and further research.

Part 2 contains the four research papers on which this dissertation is based. The first research paper investigates the factors influencing the development of the German energy transition by using a cause-and-effect analysis and elaborating their interconnections and influences. The second research paper develops a prosumer-oriented Total Cost of Ownership (TCO_P) model for the private prosumer under German market conditions who is using a photovoltaic (PV) system and a battery energy storage (BES) system. In the third research paper, this TCO_P model is extended to include the possibilities of sector coupling and an analysis of carbon emissions. In the fourth and last research paper, the private prosumer is analysed by means of a Life Cycle Assessment (LCA), whereby the environmental impacts of the different configurations of the prosumer are determined in a comprehensive manner.

The following table shows the status of the four research papers included.

No.	Title	Authors	Status
1	Causes and Effects of the German Energy Transition in the Context of Environmental, Societal, Political, Technological, and Economic Developments	Kappner, Letmathe, Weidinger	• Submitted to "Energy, Sustainability and Society" • Presented at PhD Seminar of the Chair of Management Accounting, RWTH Aachen University
2	Optimisation of Photovoltaic and Battery Systems from the Prosumer-oriented Total Cost of Ownership Perspective	Kappner, Letmathe, Weidinger	• Published in "Energy, Sustainability and Society" • Presented at UFZ EnergyDays 2018 • Presented at PhD Seminar of the Chair of Management Accounting, RWTH Aachen University
3	Financial and Environmental Potentials of Sector Coupling for Private Households	Kappner, Letmathe, Weidinger	• To be submitted to "Energy" • Presented at PhD Seminar of the Chair of Management Accounting, RWTH Aachen University
4	Life Cycle Assessment of Residential Photovoltaic and Battery Systems for Private Prosumers	Kappner, Letmathe	• To be submitted to "Renewable and Sustainable Energy Reviews" • Presented at PhD Seminar of the Chair of Management Accounting, RWTH Aachen University

Table 1: Research Papers of Dissertation

1 Introduction

1.1 Motivation of the Research Topic

Climate change is a problem that has become the focus of public discussion worldwide in recent years. In order to keep global warming within acceptable limits, the large industrial nations in particular must greatly reduce their emissions of climate-damaging gases. The Paris Climate Agreement of 2015 sets the goal of preventing global warming to rise above 1.5°C [1]. Recently, the Intergovernmental Panel on Climate Change (IPCC) reiterated the urgent need to meet the 1.5°C maximum warming target compared to the pre-industrial era in order to prevent sustainable threats to humans and nature [2].

In 2019 (before Coronavirus reduced emissions from industry and traffic in the meantime), global emissions amounted to 43 billion tonnes [3]. The energy sector accounts for a large share of emissions of climate-damaging gases. It is responsible for about three quarters of global greenhouse gas emissions. The generation of electricity and heat in particular accounts for 30.4% of global greenhouse gas emissions [4].

Germany started early to initiate measures for the conversion of electricity and heat generation to renewable energy sources (RES). Internationally, Germany was therefore seen as a leader in the energy transition [5–7]. German Chancellor Angela Merkel was dubbed the "Climate Chancellor" [8]. The German expression "Energiewende" was also adopted internationally. In recent years, however, Germany has not quite lived up to its reputation. In 2020, Germany narrowly met its target for reducing greenhouse gas emissions by 40% compared to 1990. However, this was due to the consequences of the Corona crisis, an external shock which severely restricted transport as well as production [9].

Thus, it will also be difficult in the future to achieve the next self-imposed targets. For the year 2030, a reduction of 55% in greenhouse gas emissions is to be achieved, and for 2050 a reduction of 80-95% is planned, in each case compared to 1990. The Green Party, which has had a steadily growing electorate in recent years and is running its own candidate for chancellor for the first time in the 2021 federal elections, is even calling for a 70% reduction in greenhouse gas emissions by 2030 and complete climate neutrality before 2050 [10]. The targets set are derived from European Union (EU) agreements and the United Nations (UN) Framework Convention on Climate Change. They are bindingly defined in the German Climate Protection Act of December 2019 [11, 12].

As on a global level, the energy sector, specifically electricity generation, is also of central importance in Germany for achieving the aforementioned goals. In addition to the challenging replacement of fossil fuels (mainly hard coal, lignite and gas), Germany has committed to ending nuclear power generation, which is a controversial energy source but carbon dioxide (CO_2)-neutral. In 2011, the German government decided to take all nuclear power plants off the grid by the end of 2022 [13]. In addition, in 2020 the phase-out of coal-fired power generation was legally set for 2035, but no later than 2038 [14].

Both the climate protection goals and the set ends of the currently still heavily used conventional technologies for power generation are leading to the inevitable need to drastically expand the capacities of power generation from RES. In general, some authors see the energy transition not only as a necessity but also as an opportunity to make Germany future-oriented and sustainable [15]. Nevertheless, as things stand today, it is not possible to say for sure whether Germany will achieve its set target of a 65% share of RES in electricity generation by 2030 [16]. At present, Germany is not an international leader of energy transition, but average at best [17].

Renewable energies were promoted separately for the first time in Germany with the Electricity Feed Act (Stromeinspeisungsgesetz) of 1990, which separately regulated the feed-in of electricity from RES. This was followed by market liberalisation in 1998, which, however, could not prevent Germany from still having one of the highest electricity prices in Europe [18]. Since 2000, the Renewable Energy Act has been in place, which not only regulates the feed-in of electricity from RES, but also contains a wide range of financial support for RES financed by a levy, which has been regularly adjusted over the last 20 years.

Especially regarding the financial subsidies, there were some points of criticism due to the priorities chosen. For example, in 2010 PV supplied only 9% of the electrical energy, but received 40% of the subsidies paid [19].

Currently, the production of one kWh of electricity causes an average emission of 489 g CO_2 equivalents [20]. One factor to further reduce this value and increase the share of RES in electricity production is to further focus on decentralisation of electricity generation. The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety focused on this implementation in a special way from 2010 onwards, together with the Federal Ministry for Economy and Energy's commitment to the expansion of storage systems [19].

The decentralisation of renewable electricity generation is mainly driven by promoting the so-called prosumer [21]. In general, a prosumer is a person or a household entity that consumes electricity (consumer) and at the same time also generates electricity for self-consumption and feeding into the grid (producer) [22]. In addition to direct self-consumption of self-generated electricity, storage or additional load can be used to increase the so-called self-consumption rate [23]. Private prosumers are usually households which generate electricity with a PV system and optionally use a BES system [22, 24].

1.2 Research Model and Associated Research Questions

The energy transition is a comprehensive process intended to help limit climate change and keep global warming to a certain level. In addition to the finite nature of the fossil resources used to date, it is therefore primarily environmental aspects justifying this drastic change. Socially and politically, there is overwhelming agreement that a continuation of the damage to the environment and climate caused by the emission of greenhouse gases is unacceptable.

The energy sector offers a great deal of scope for reducing these emissions of climate-damaging gases to the necessary extent or for avoiding them altogether. This change is challenging. The original system is centralised generation from fossil and nuclear energy sources. This system has to be transferred to a generation from RES, which, however, is characterised by a decentralised structure. At the same time, an affordable and always reliably available electricity supply is indispensable for society and the economy.

The energy sector and electricity generation in particular are strongly influenced by regulation. Thus, the German energy transition is also guided by regulations, or in many cases enforced, as there is no voluntariness.

One building block of this regulatory energy transition is the private prosumer, which has received a number of financial subsidies and is a “product” of the multi-layered process of the energy transition. The question is whether and in which constellations the prosumer model is financially worthwhile, which is an important condition for its widespread application. In addition, it must be clarified to what extent environmental benefits arise from the private prosumer, as this is fundamentally the goal or purpose of the energy transition. This is not only about the greenhouse gases in focus, but possibly also about other environmental damages that are accepted.

Specifically, this dissertation addresses the following overarching research question:

Overarching Research Question

Which effects do economic, environmental, societal and technological impact factors have on the private prosumer's financial benefit and ecological footprint in Germany?

The research model described below (see Figure 2) was developed to address the overarching research question. Basically, the model distinguishes between an overarching perspective and the specific perspective of the prosumer. In the overarching perspective, the fundamental impact mechanisms of the German energy transition are first examined. The prosumer's perspective illuminates the specific situation of a (new) actor in the economic and regulatory environment of the energy transition.

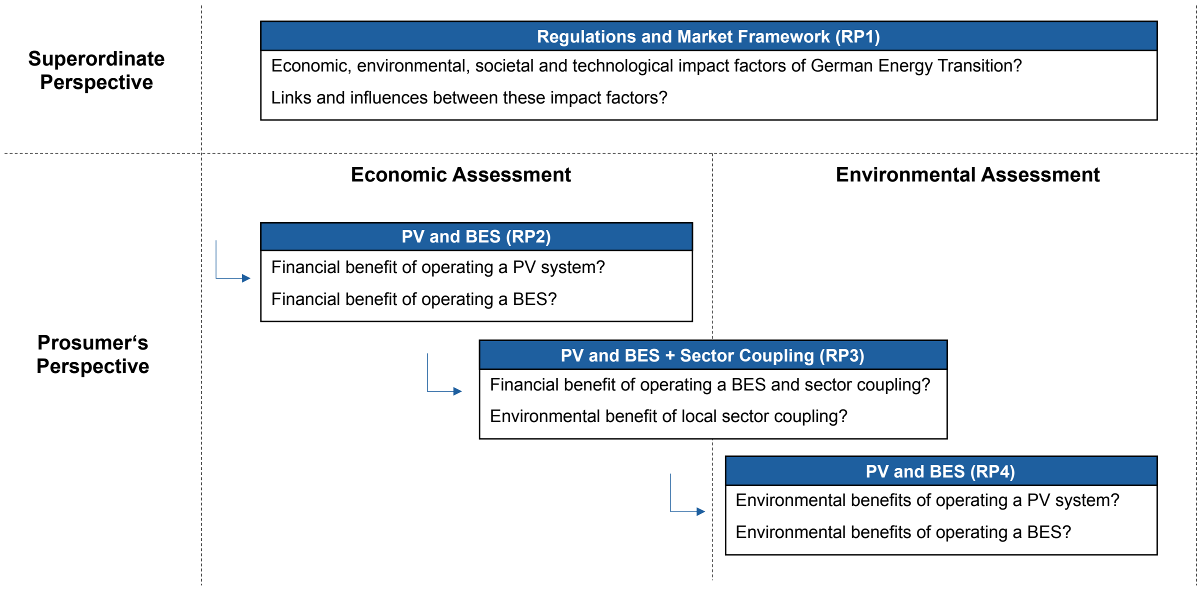

Figure 2: Dissertation Research Model

In the overarching perspective, the regulations and the market environment of the German energy transition are first examined. The influencing factors are subdivided into four categories, i.e., economic, environmental, societal and technological, and they are elaborated over time. One focus is on the connections and influences between the categories, which are usually always present, but can be made particularly clear in the area of energy.

The question of the effect of the previously identified impact factors on the private prosumer's performance leads to the transition to the prosumer's perspective. The evaluation takes place in the economic and environmental spheres. Here, economic efficiency is the central criterion for the will to implement new investment. The environmental assessment examines the actual contribution to the core objective of protecting the environment.

First, the private prosumer is economically evaluated in the configuration PV system with optional BES. The economic evaluation is carried out by determining the financial impact of different configurations of the prosumer model, as this is the economic category that is of interest to private individuals. Specifically, the financial advantageousness of operating a PV system is examined, supplemented by the opportunity of increasing this by operating a BES.

The concept of sector coupling – linking the electricity, heat and mobility sectors – is a way to increase the use of RES and to deal with volatilities in generation. This concept is also available to the prosumer. After the initial investigation, the question arises as to what extent the prosumer can improve their financial performance by applying sector coupling, especially with regard to the advantageousness of a BES. It is investigated whether the optimal configurations of the prosumer change with regard to financial benefits. In addition, a first environmental assessment is carried out. The savings in CO_2 emissions achieved through the application of local sector coupling are determined. These savings are also put in relation to the financial results.

As already explained, the concept of energy system transformation is fundamentally based on the goal of protecting the environment. In this respect, all measures always need to be critically examined in terms of their actual contribution to this goal. This should also be examined in relation to private prosumers. Therefore, in conclusion, the use of PV and BES for private prosumers is subjected to a comprehensive environmental assessment by means of an LCA. This also includes any environmental impacts at the expense of which greenhouse gas (GHG) savings may be achieved.

The four stages of the model described above were examined in this dissertation in four separate research papers, with each paper being assigned to one stage.

Research Paper 1 (RP 1) examines the impact factors and mechanisms of action in the German energy transition. The economic, ecological, social and technical impact factors are elaborated, with a focus on their interactions. Furthermore, the development of the regulatory environment for actors on the energy market is considered in order to illustrate the challenges for established companies in particular.

The research questions of research paper 1 are:

1st Research Question of Research Paper 1

What effects have played a substantial role in the German energy transition and how have they interacted?

2nd Research Question of Research Paper 1

What regulations have influenced companies in the energy sector during the German energy transition?

After the impact factors and their effects on the actors have been analysed following the previous questions, the focus in the further papers is placed on the private prosumer.

RP2 first deals with the financial performance of a private prosumer. For this purpose, a prosumer-oriented TCO model is developed based on preliminary work. Using real-world data, the financially optimal configurations from the prosumer perspective are determined. In the process, the regulatory framework conditions come into play in a decisive way.

Specifically, the following two research questions are addressed in RP2:

1st Research Question of Research Paper 2

Which adjustments need to be added to existing TCO models in combination with PV-BES-systems based on detailed real-world data sets and how can the TCO_P be calculated for different PV systems in combination with BES systems under different usage scenarios?

2nd Research Question of Research Paper 2

What is the most cost-effective option for a PV-BES-system from the user perspective under consideration of German market conditions and how are the results influenced by German legislation for feeding-in electricity from renewable energy sources?

Building on the results of the previous research questions, the question arises as to how to further improve the financial performance of the prosumer.

RP3 investigates the opportunities to improve the benefits of PV and BES for the private prosumer by applying the concept of sector coupling. Furthermore, it is also about increasing the self-sufficiency rate itself, as this is seen by many prosumers as a goal in its own right. To this end, the use of heat pumps and heating rods instead of gas heating and the charging of a battery electric vehicle (BEV) are included in the scope of consideration.

The research questions of RP3 are:

1st Research Question of Research Paper 3

Can the use of a battery energy storage (BES) system become financially advantageous for a private prosumer when considering all the energy needs of a domestic household?

2nd Research Question of Research Paper 3

What improvements in self-sufficiency can be achieved if further energy demands in a domestic household are electrified?

After considering the configuration options of the private prosumer and the influence of the regulatory framework, RP4 examines the environmental impacts of the prosumer. The goal of all energy transition measures should be to reduce the environmental impact of energy production and use. Using LCA, precisely this is examined in relation to the prosumer. However, not only the often solely considered GHG emissions are taken into account, but also other damage categories in accordance with the principle of a comprehensive LCA.

The following research question for RP4 is derived from these objectives:

Research Question of Research Paper 4

Can a domestic household reduce its environmental impact from electricity consumption by using a photovoltaic system in combination with a battery energy storage system?

Figure 3 summarises the titles, methodologies and objectives of the papers included in this dissertation.

	Paper 1	Paper 2	Paper 3	Paper 4
Title	Causes and Effects of the German Energy Transition in the Context of Environmental, Societal, Political, Technological, and Economic Developments	Optimisation of Photovoltaic and Battery Systems from the Prosumer-oriented Total Cost of Ownership Perspective	Financial and Environmental Potentials of Sector Coupling for Private Households	Life Cycle Assessment of Residential Photovoltaic and Battery Systems for Private Prosumers
Methodology	Cause and Effect Analysis Literature Analysis	Total Cost of Ownership Simulation Modelling	Total Cost of Ownership Simulation Modelling	Life Cycle Assessment
Objective / Results	Economic, Environmental, Societal and Technological Factors of Energy Transition	Financial Assessment of a Prosumer (PV & BES) under German Market Conditions	Financial (and Environmental) Assessment of Sector Coupling for a Prosumer (+ Heat Pump & BEV)	Assessment of Environmental Impacts of a Prosumer (PV & BES)

Figure 3: Overview Dissertation Paper

1.3 Contribution

The following chapter describes the particular scientific contributions of the four underlying research papers of the present dissertation.

Paper 1

RP1 summarises the most important events and decisions of recent decades that have influenced the transition of the German energy system. The factors are grouped in categories and analysed according to their cause-and-effect relationships. Their interdependence is analysed in an Ishikawa diagram. In addition, the opportunities and risks as well as the obstacles including the relevant path dependencies of the energy transition are considered from different angles. The implementation of some of the possible solutions is being hampered by society and politics; others are not yet technologically feasible and need further research and development. To sharpen these perspectives, they need to be considered separately at first, to be merged and then to be set into context of each other. This can help to identify the best way to continue with (Germany's) energy transition and to understand why, for instance, big German energy producers are struggling with their business models.

The influences on the energy sector are manifold and can be attributed to society and politics, economy, environment and technology. Their interdependence is not obvious at first glance at every point. The paper analyses dependencies and connections and also reflects that not every approach to sustainability or Corporate Social Responsibility (CSR) is measurable or even yields a positive economic output. However, to overcome economic disincentives, politics can provide incentives to induce desired changes. On the other hand, private and corporate consumers can exert great influence on the energy sector by making decisions modifying their consumption patterns and actively participating in social movements and influencing politics. The associated developments also point towards approaches for the future progress of energy system transformation. At the same time, the energy system has an enormous inertia that makes it difficult to implement new business models. For companies, an understanding of their environment, considering all stakeholders, is fundamentally indispensable.

Paper 2

RP2 makes a contribution by providing a TCO_P model based on the existing literature, which closes the identified research gap, by presenting a comprehensive consumer-oriented calculation of a PV-BES-system with real data and different realistic household sizes. The article positions the prosumer as the owner of the system at the centre of our analysis. The calculations provide a realistic outcome of the aspects of using self-produced electricity, storage and connection to the grid, presenting the opportunity to feed-in and use electrical energy. A TCO_P model was developed for a 20-year lifetime period under realistic usage conditions with the possibility of analysing changes in the discount rate, inflation, increasing energy efficiency, etc. Based on this, the model was applied to real market data. Thus, results were obtained for different constellations of household size, PV system capacities and BES capacities. Using discrete optimisation, RP2 determines the financially best constellation for different household sizes. It also relates the calculations' results to the corresponding self-sufficiency rates. Although the analyses focus on the German energy market, the development of the extended TCO_P methodology can also be adapted to other market conditions or restrictions. Answering the questions above contributes to a more independent and holistic economic evaluation of participating in the energy transition in Germany as a prosumer. Moreover, the results help to identify relevant improvement potential for governmental policy makers when setting incentives and for producers when designing prosumer-oriented products.

Paper 3

Research paper 3 investigates a decentralized solution for sector coupling, with the option of generating and using electricity as the only energy source for each of the three domains, i.e. heating, electricity and mobility. While the focus is on financial consequences, there are considerations of additional aspects like self-sufficiency, local consumption and carbon emissions too. The self-sufficiency rates of the scenarios highlight the importance of these parameters in the transition towards prosumerism.

As the analyses address the detailed household level, there is a clear distinction between this work and other studies in this area, which only refer to average quotas and which calculate average values that cannot be deployed realistically in a single facility.

This paper investigates whether a PV-BES-based prosumer model can pay off when considering additional load such as heating, hot water, and mobility demands.

Furthermore, the relevant authorities need to decide which energy use by private households is considered desirable and worthy of support. The advantage of this study is the use of real data instead of theoretical considerations, which constitutes a major improvement over previous research. The paper contributes in this respect by showing the effects which can be achieved by changes in government subsidies and which sustainable options could be promoted with additional financial support.

Paper 4

There is a research gap in the field of LCAs of a private prosumer. While comprehensive studies have been conducted partially on separate assets, no overall picture has yet been created that would subject the assets of a private prosumer to LCA in their real application.

Therefore, RP4 developed a model that combines the results and findings of various LCA studies on PV systems and battery storage with the results of previous research on the financial room of manoeuvres and the self-sufficiency of private prosumers for the first time. Specifically, the extent is investigated to which a prosumer can generate added value in terms of various environmental impacts with his assets during the use phase which exceeds the impacts resulting from production and final recycling.

By this, RP4 provides a sound basis for decision-making in a politically, socially and economically important topic for both political and private decision-makers. Thus, it paves the way to making decisions on a more differentiated fundament than before. In addition, the paper initiates further research that follows technical developments in the field of private energy consumption and generation from an LCA perspective.

2 Theoretical Background and Current State of Research

2.1 Structural Change of the Energy System

The electricity generation and distribution system is undergoing a comprehensive transformation due to the increase in renewable electricity generation. The system used to be designed as a top-down model. Electricity was (almost) exclusively generated centrally using conventional energy sources. The generated electricity was fed into the grid at the High Voltage level and transported to the consumer via the Medium Voltage level up to the Low Voltage level. Individual industrial consumers are also already connected to the grid at higher levels.

The introduction of renewable electricity generation brings about two crucial changes: Feeding into the grid via generating units occurs at all levels of the grid. In addition, storage units are increasingly added at all levels to compensate for the volatility of renewable generation. This results in a new system structure. The electricity is routed bidirectionally; the clear separation between producers and consumers is abolished. The result is a multi-level exchange system.

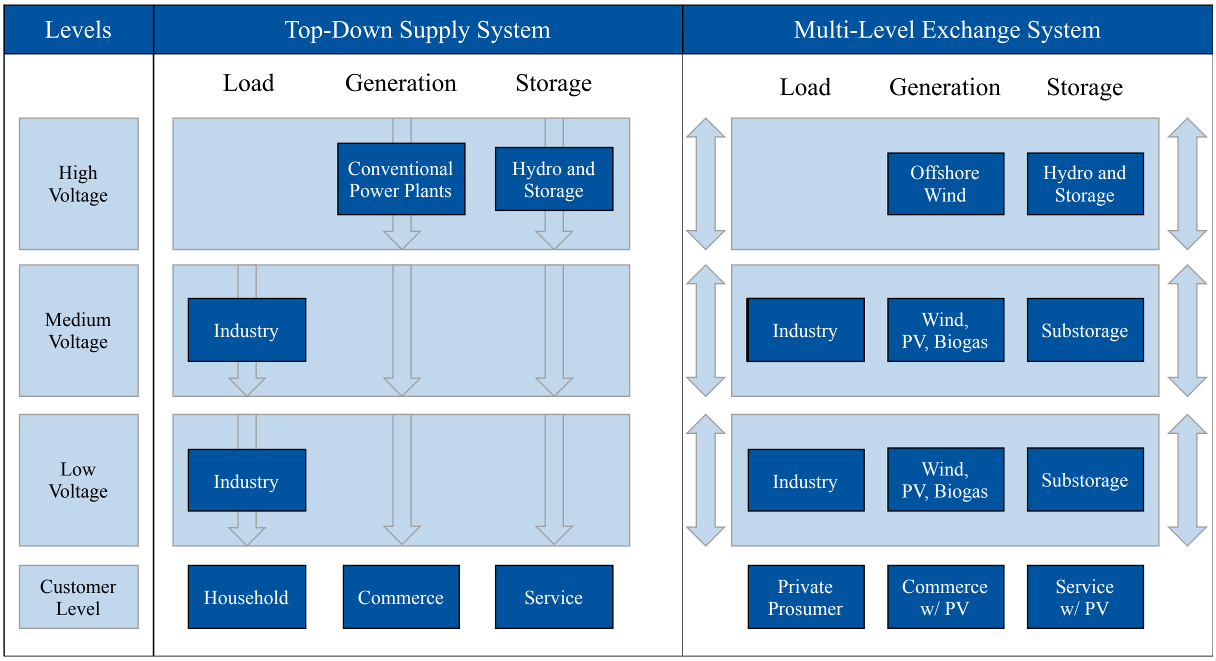

Figure 4: Transformation of Electricity Supply System

Figure 4 illustrates the former top-down model of the electricity supply on the left side, while new participants and multi-level exchange structures are emerging today and in the future (right side). The European Parliament supports the goals of lowering the connection costs and ensuring an equal treatment of consumers in rural and city areas [25]. Since energy generation in a bottom-up market model is a ground-breaking change, the new situation for consumers and prosumers needs to be evaluated financially [26]. However, not only will the electricity market change because of this new model; direct current (DC) generation (PV), the need for energy storage, and new connection technologies will also fundamentally affect the electricity market.

2.2 Private Prosumers

The *prosumer* is defined as a consumer who also generates electricity for others [27]. For efficiency reasons, it is common to use storage systems and additional electrical load [23]. Often, prosumers are organized into private households and use small-scale PV- and/or battery systems [24, 27]. Figure 5 shows a schematic representation of such a private prosumer including the application of the concept of sector coupling described below.

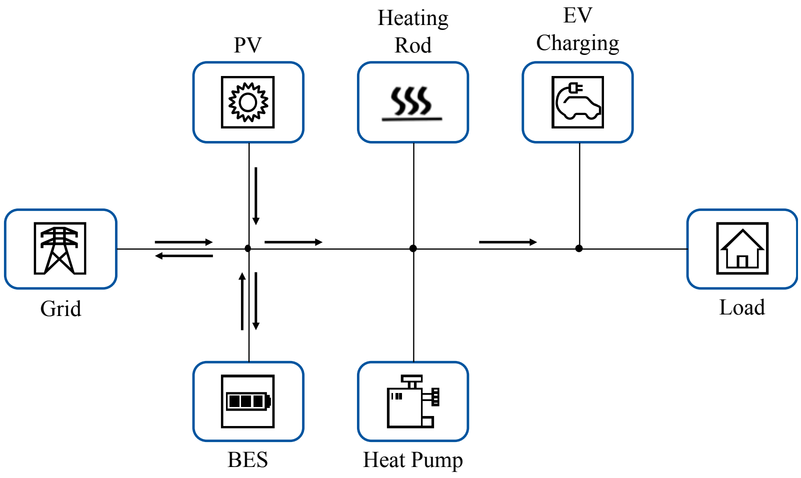

Figure 5: Schematic Representation of a Private Prosumer

For the energy transition in Germany, prosumers play an important role [21] by generating electricity over many decentralized sites. When producing electricity from renewable sources – in particular from PV systems – not only are prosumers important for future smart grids [28], they can also help to reduce carbon emissions by storing and consuming their self-generated energy [21, 29]. However, the prosumers, as decentralised generation entities, will have to be integrated into the future grid in order to support the system's stability and efficiency [30].

The transition of the German energy system is a huge challenge for policy makers and is absolutely necessary if emissions are to be reduced. However, this transition cannot be successful unless a broad participation of energy producers and energy consumers is achieved and their efforts are well coordinated and aligned with each other [31–33].

Hence, small-scale energy generation and storage is relevant not only from a technical but also from an economic perspective [34]. Locally stored electricity can be a valid option for buffering renewable energy in order to compensate gaps between local demand and local generation [34, 35]. In Germany, the installed PV capacity increased drastically from 0.114 GW in 2000 to 49.016 GW in 2019 [36–38]. Considering that PV is often used for local electricity generation, storage options have become more relevant. Even if the average subsidy for feed-in electricity per kWh is decreasing over time [36], some analysts see an increasing disposable income for prosumers [21].

In order to turn more consumers into prosumers, the concept of prosumerism needs to be financially attractive. In addition, a high level of autarchy can be a vital benefit of becoming a prosumer, as many consumers aspire to use a large part of their own electricity [21].

The Table 2 provides a comprehensive overview of the research on the prosumer.

#	References	Business Adminis-tration		Economic	Technical	PV	BES	Description
		other	TCO					
1	Akter. Mahmud, and Oo 2017 [39]	x			x	x	x	• solar photovoltaic units and battery energy storage systems • levelised cost of energy along with reductions in carbon dioxide emissions and grid independency • in Australia
2	Bertolini, D'Alpaos, and Moretto 2016 [40]	x	x			x		• impact of a PV system for micro-grids
3	Bortolini, Gamberi, and Graziani 2014 [41]	x				x	x	• economic model for grid-connected PV and BES system in Italy
4	Comello and Reichelstein 2016 [42]	x				x		• economic efficiency of PV in the U.S. • remuneration system
5	Cucchiella, D'Adamo, and Gastaldi 2016 [43]	x				x	x	• profitability of PV systems • profitability of energy storage in a mature market in Italy
6	Kamankesh and Agelidis 2017 [44]	x		x		x		• optimising the management of the grid with high share of RES and V2G
7	Kaschub, Jochem, and Fichtner 2016 [45]	x				x	x	• developments of battery storage technology with PV • generation mix of utilities, use of the distribution grid, and electricity price
8	Klise, Johnson, and Adomatis 2013 [46]	x	x			x		• TCO for PV systems in the U.S. • discounted cash flow
9	McDowall 2017 [47]				x	x	x	• significance of BES for the autarchy of micro-grids
10	Naumann et al. 2015 [48]	x			x		x	• costs and revenues for BES • techno-economic model for revenues
11	Rosen and Madlener 2016 [49]			x				• changes in market regulations • enable trading of energy for prosumers
12	Rylatt et al. 2013 [50]			x	x			• market model • prosumer is embedded in an aggregator structure
13	Uddin et al. 2017 [51]	x				x	x	• photovoltaic systems integrated with lithium-ion BES • in UK
14	Vosoogh et al. 2014 [52]	x		x	x	x	x	• optimising the energy flow in a micro-grid
15	Zhang et al. 2016 [53]	x				x	x	• three different types of BES • in Sweden

Table 2: Overview of the Literature on Prosumers

According to the table above, in the existing literature there are various investigations in the fields of PV and BES and their financial aspects. However, some work is limited to the consideration of PV systems only [40, 42, 46]. Other research which also considers PV and BES models focusses on countries and markets outside Germany, such as Australia [39], Italy [41, 43], Sweden [53] and the United Kingdom [51]. Moreover, previous studies usually only consider one single household size [45] or assume (partially) already installed systems [48]. Many studies work with linearised prices for assets and services, whereby such a procedure does not reflect exactly the conditions for a potential prosumer.

Furthermore, there are investigations into how the prosumer's configuration can be further expanded.

Battery storage can significantly increase the energy autonomy [54]. Moreover, apart from the analysis of generating and storing electricity, previous research has investigated the increase in the share of own and self-generated energy by adding more consumption points. Toradmal, Kemmler and Thomas (2018) [55] introduced a heuristic optimisation method for operating with different electricity-consuming assets such as a heat pump. They found that, even with a storage battery, not more than half of the demanded electricity can be covered by locally generated electricity using demand site management tools and switching off the heat pump in peak hours (from 4:00 p.m. to 7:00 p.m.). The research of De Coninck et al. (2014) [56] studies a microgrid of 33 single-family dwellings in Europe managing the demand of electricity and heat in combination with domestic hot water production. The study shows that PV inverter shutdowns can be strongly reduced by integrating electricity and heating.

Consequently, the concept of sector coupling can be a way to improve the performance of the prosumer. Sector coupling refers to the idea of connecting the sectors of electricity, heating and transport. The concept includes the use of energy converters and storage solutions, allowing renewable electrical power to be used to reduce carbon emissions in the other sectors. Furthermore, transmission losses can be reduced and the throttling of power generation in peak times can be avoided by increasing the energy consumption through additional consumers [57].

As one third of the energy demand is created by the household sector [58], sector coupling in private households is an essential option for decreasing the demand for fossil energy sources. New technologies are arising that integrate demand for electricity, heat, and cooling [59]. One of the most discussed solutions is that of running heat pumps as energy buffers on the prosumer level [55]. In peak times, heat pumps can convert electricity into heat for later use as thermal energy. This technology is a promising addition to the prosumer concept for managing heating demand [60].

In addition to the technical and economic assessment of the private prosumer, an environmental assessment is also necessary for a complete picture, as already mentioned in chapter 1. After all, the purpose of the prosumer is to contribute to the reduction of environmental pollution. Only if this goal is achieved, the prosumer itself and any subsidies and regulations with which it is supported have a justification. Despite the relevance of such studies investigating this aspect, to our knowledge there is no research in the current literature that comprehensively examines the private prosumer in terms of their environmental impacts. Only studies on individual assets of the prosumer can be found. In the following, an overview of this existing research is given.

The use of PV systems has been common practice for several years, so today there are numerous studies that deal with the LCA of PV systems. Leading and often quoted studies of the last years are those by Fthenakis and Raugei (2017) [61], Gerbinet, Belboom and Léonard (2014) [62], Hong et al. (2016) [63], Ludin et al. (2018) [64] and Wu et al. (2017) [65].

The reviews in this area show that the leading studies have arrived at comparable results, but they are usually limited to the consideration of the so-called energy payback time (EPT), the time it takes for a PV system to produce the energy that was needed for its own production. The global warming potential (GWP) balance is also examined. The consensus of the studies is an EPT of 1 to 3 years, with a clearly positive GWP balance in all cases.

Furthermore, there are a few studies that present more comprehensive LCAs of PV systems with respect to several impact categories: Alsema and De Wild-Scholten (2006) [66] compiled the first reliable LCI databases for PV module manufacturing by conducting a case study with 11 PV manufacturers from the USA and Europe. Based on their own data, they determined an energy payback time for PV modules of about two years and pointed out significant savings in CO_2 emissions compared to conventional energy sources. Fthenakis and Kim (2011) [67] investigated four commercial PV technologies and delivered detailed descriptions of the material and energy flows of these devices. De Wild-Scholten (2013) [68] updated data from Alsema and De Wild-Scholten (2006) [66] and determined energy payback times from one to two years and a carbon footprint of 20-81 CO_2-eq/kWh. Fu, Liu and Yuan (2015) [69] and Chen et al. (2016) [70] each delivered a comprehensive LCA of PV systems describing material and energy flows in the manufacturing process and presenting resulting environmental impacts in common impact categories.

Despite the End-of-Life (EoL) phase usually being considered in an LCA, the final disposal of the PV system is not considered in the studies mentioned above. However, this topic will become increasingly relevant in the future. Based on the number of plants already installed and the expected further development, up to 10 million tons of PV panels to be disposed of can be expected by 2050. This figure shows the importance of considering adequate recycling. However, only the study by Latunussa et al. (2016) [71] has investigated the PV recycling process using an LCA.

There is a lack of LCA studies on prosumers as described above, and one reason for this is believed to be the insufficient amount of data in the BES area. One opportunity to overcome this lack is to refer to LCA studies on batteries of BEVs and plug-in hybrid electric vehicles (PHEV) in order to acquire data on BES respecting technical differences of these application areas. The review by Peters and Weil (2018) [72] provides a very good overview of the various studies. Based on this, there are some relevant studies by Zackrisson, Avellán and Orlenius (2010) [73], Majeau-Bettez, Hawkins and Strømman (2011) [74], Ellingsen et al. (2014) [75] and Kim et al. (2016) [76] as a valuable basis for such investigations.

Similarly to the field of PV systems, the final recycling of batteries has not been considered by most of the leading studies. However, there is one relevant study by Cusenza et al. (2019) [77] that can be referred to. There, both the recycling process itself and credits resulting from the reusability of extracted resources are considered.

3 Research Methodologies

Various scientific methodologies were used to address the individual research questions in the papers on which this dissertation is based. In the following sections, the methods Cause-and-Effect Analysis, Simulation and Modelling and Life Cycle Assessment are explained and classified in terms of their applications in the RPs and in answering the overall research question.

3.1 Cause-and-Effect Analysis

The methodology of cause-and-effect analysis is applied in RP1 of this dissertation. It is used to work out the economic, environmental, societal and technological impact factors in the transformation of the German energy system.

The cause-and-effect analysis is a tool which describes relationships between causes and their effects. Originally, the cause-and-effect diagram was invented and developed by Kaoru Ishikawa as a tool for quality management. Therefore, it is also called Ishikawa diagram [78].

An Ishikawa diagram usually has the following structure: The core problem to be considered is positioned at the top of the diagram. Subsequently, the main factors influencing the problem to be investigated are identified and installed as branches along a main axis. The resulting construct resembles the skeleton of a fish, which is why the diagram is also called fishbone diagram. In a second step, the main influencing factors are assigned to subcategories which branch off from the large bones as small bones [79]. Thus, an Ishikawa diagram can be used to present the search for and the development of the causes of a problem in structured way [78, 80]. Over the course of time, the Ishikawa diagram has also been adopted by other disciplines to explain complex and multi-causal relationships. The use of the method in various research areas shows the versatile possibilities of applying of the Ishikawa diagram [80–83].

Hence, Ishikawa diagrams are also suitable for explaining complex developments such as the evolution that has led to the transition of the German energy system. Even though the distinction between cause-and-effect is not always clear, the diagram can show how interdependences between different factors have affected actions and reactions by multiple stakeholder groups and how they have fostered developments.

In RP1, the main factors examined are the three pillars of sustainability and, as a fourth factor, technological developments, which determine the structure of the cause-and-effect diagram.

As all of the four perspectives have contributed to the energy transition in Germany within the last decades, they are first analysed separately and are then combined in an overall Ishikawa diagram. This approach enables not only a better understanding of the transition of the energy system in Germany but also provides the opportunity to draw conclusions for future trends and for developments in other countries.

3.2 Simulation and Modelling

In RP2 and RP3 of this dissertation, financial evaluations of the private prosumer model are carried out, on the one hand, with PV and BES and, on the other hand, with different possibilities of sector coupling. For this purpose, the respective prosumers are modelled and simulated in both RPs using real-world data. Models are developed with all impact variables. Taking into account all relevant variables within the framework of consideration, all payment flows associated with the prosumer activity are then derived. A distinction is made between capital expenditure (CAPEX) at the beginning of the period under consideration and operational expenditure (OPEX) during operation.

The development of the models and the evaluation of the derived cash flows by comparable key figures is carried out using the TCO method by means of dynamic investment calculation. By applying the method from the perspective of the prosumer, the concrete investigations are prosumer-oriented TCOs.

The TCO method analyses activities and related cash flows within an investment's useful lifetime [84]. It has a broad scope and also includes pre-purchase costs, for instance [85, 86]. This comprehensive approach distinguishes the TCO from other comparable methods [87].

To investigate a long-term investment such as in a PV-BES-system, the TCO concept is particularly suitable because it is designed to be activity-based and it informs the entity – in this case the prosumer who owns the PV-BES-system – about the economics of past, current and future decisions [85, 88]. Furthermore, the TCO concept is logical and easy to understand, especially as it focuses on the total cost of an investment [84]. TCO shifts the focus from the purchase cost to the total cost, and is therefore more suitable for making informed decisions [89]. This means that TCO is not only a purchasing tool but also a philosophy [85] which helps a purchaser to understand the real costs of buying a particular good from a particular supplier [84, 85]. In this case, the paper provides objective information for those customers who want to become prosumers by investing in a PV and/or a BES-system. Furthermore, the TCO concept allows the user to understand, analyse and manage the financial consequences of purchased items in a progressive and systematic way [84]. Specifically, the TCO method allows the user to consider such elements as order placement, research and qualification of suppliers, transportation, receiving, inspection, rejection, replacement, downtime caused by failure, disposal costs, etc. [85, 90]. Thus, the TCO concept displays more than just purchase prices, by considering the costs of the entire product-life, such as those related to service, quality, delivery, administration, communication, failure, maintenance and so on [90, 91]. Beyond that, the TCO approach takes into account the transaction costs [89]. However, as the TCO concept requires detailed accounting and costing data, the lack of readily available data might be a limitation [85]. Furthermore, the "TCO concept requires firms [or entities] to consider those activities that are causing them to incur costs. By analysing flows and activities within each process, a firm can identify which activities add value, and which do not" [84]. Hence, the user of TCO_P is the prosumer conceptualising the system that they are willing to invest in [92].

The TCO_P calculations in RP2 and RP3 are based on comprehensive models including all cash flows related to electricity consumption, generation and storage using a dynamic investment appraisal method – the Net Present Value (NPV) method. The basic structure of the annuity calculation based on an investment's NPV is shown in Equation 1.

$$C_{TCO_P} = C_{NPV} \frac{(1+i)^t * i}{(1+i)^t - 1} \tag{1}$$

C_{TCO_P} characterises the annual prosumer-oriented total cost of ownership, hereinafter also referred to as annuity. C_{NPV} is the Net Present Value, t is the index for the period and i is the rate, with which all payments are discounted. The costs are considered on an annual basis, as costs per year are usually calculated in the private energy sector.

The net present value C_{NPV} is determined by adding up all observed cash flows, which are discounted on an accrual basis, as shown in Equation 2.

$$C_{NPV} = C_{Capex} + \sum_{t=1}^{T} \frac{C_{Opex,t}}{(1+i)^t} \tag{2}$$

C_{Capex} is the capital expenditure, $C_{Opex,t}$ is the operational expenditure in period t, T is the whole period under review. The NPV is calculated with different parameters: internal and external ones.

3.3 Life Cycle Assessment

RP4 in this dissertation uses the Life Cycle Assessment methodology to answer its research question. Using this methodology, this paper assesses the environmental impact of a prosumer, taking into account the entire life cycles of the assets used by the prosumer.

The concept of LCA as defined in ISO 14040 [93] and ISO 14044 [94]. LCA is a technique used to determine the various environmental impacts of a product throughout its overall life cycle, from production through all aspects of use to disposal. ISO 14044 provides a basic procedure for this, but not an exact description. According to Figure 6, there are four stages in the preparation of an LCA:

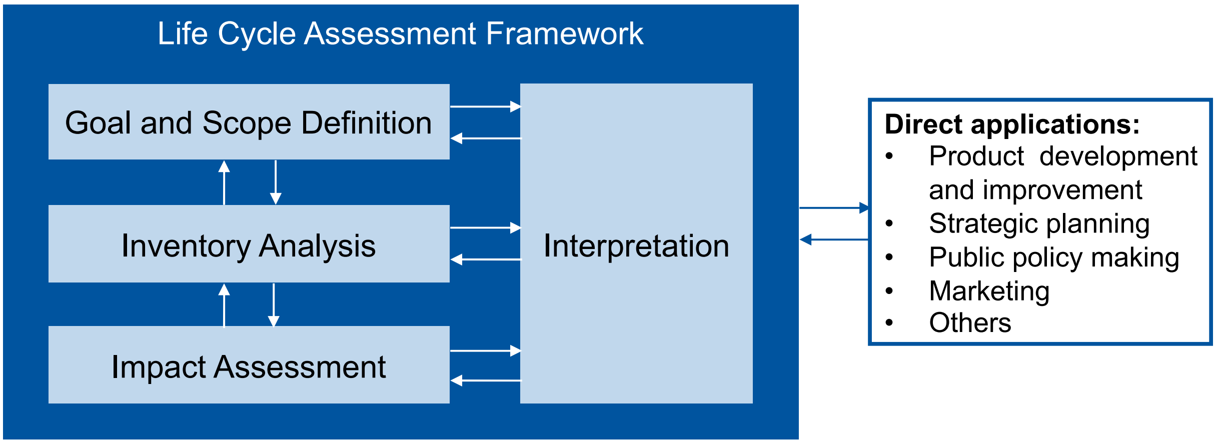

Figure 6: Structure of the Life Cycle Assessment Methodology [93]

Step 1 "Goal and scope definition" defines the exact object of consideration of the LCA. In addition, it describes the steps of the product life cycle to be considered and defines a functional unit related to the results.

Step 2 "Life Cycle Inventory Analysis" (LCI) describes all relevant material and energy flows of the product system. In particular, this includes the interaction with the environment: the extraction of raw materials and the release of emissions.

Step 3 "Life Cycle Impact Assessment" (LCIA) evaluates the material and energy flows determined in the LCI according to their environmental impacts in various categories. For this step, a comprehensive database is required that assigns an impact to all material and energy flows in the various assessment categories of the LCA.

Step 4 "Interpretation" presents the results of the LCA, examines them for sensitivities, and carries out a critical interpretation. This might include a comprehensive evaluation of the results including the derivation of decision guidelines.

Specifically, this methodology is applied in RP4 to the PV system and the BES of the prosumer. In addition, the electricity drawn from the public grid is also assessed. In step 1, the same observation framework is chosen for the prosumer as in the previous RPs in order to ensure comparability of the results across the entire dissertation.

In steps 2 and 3, different data sources are merged. For PV systems, there is already a broad literature base in the field of LCA, from which data adapted to one's own framework of consideration can be extracted after differentiated analysis. For BES, on the other hand, such a basis is not (yet) available in the literature. Nevertheless, there is a broad literature base in the field of LCA for batteries of BEVs. Thus, the data for BES can be extracted from this, taking into account the technical differences between the battery types. In addition, the evaluation of electricity from the public grid is carried out using the ProBas database of the Federal Environment Agency (Umweltbundesamt).

Finally, step 4 fulfils the contribution of RP4 to this dissertation. With a differentiated view, the ecological footprint of the private prosumer is assessed and classified.

4 Key Findings and Implications of the Different Research Papers

4.1 Research Paper 1

RP1 analyses the process of the German energy transition using cause-and-effect analysis to identify the economic, ecological, societal and technological factors and to examine their interactions. The following findings are obtained.

All four described factors, economic, ecological, societal and technological, have impacted the German energy transition. The interactions between the influencing factors were considerably high.

Political measures and regulations have been the decisive drivers of changing the energy market. In turn, political action in this area has been influenced by two factors: economic demands on the central element of energy supply and social currents that have had a long-term impact by processes forming opinions in political parties and election results.

As mentioned before, environmental influences alone have not driven the process forward. However, individual environmental incidents have either been the impulse or the final trigger for social and political processes.

For several decades, the energy companies had relied on operating large centralized power plants. This approach was supported politically and was intensively promoted, especially in the case of nuclear power generation. As the political will shifted towards renewable energy, the framework for generators was gradually transformed. The Electricity Feed Act of 1990 and the market liberalisation of 1998 left the producers mainly untouched, so they stuck to their established strategies. It was not until the Renewable Energy Act in 2000 and the exemption of renewable energies from the Merit Order that the energy companies were affected. At the same time, the nuclear phase-out was being prepared. Despite both developments, the energy companies held on to their sources of revenue and only started to convert to renewable energies after a long delay.

Overall, the following four findings are pointed out:

Finding 1:

Environmental disasters and other environmental incidents have been triggers in Germany's energy transition process.

Finding 2:

The sector of energy generation is heavily driven by political regimentation. The developments are mainly influenced by political requirements.

Finding 3:

Political requirements and legal regulations have been determined by macroeconomic and societal demands. Following these factors, the political objectives have undergone a consistent conversion over time.

Finding 4:

Energy companies had followed the tendencies determined by political decisions and regulations, as well as subsidies for a long time, but then missed the chance to properly and timely adapt their business models.

In conclusion, waiting for a technological leap before implementing a fully renewable energy system is not promising. This study has identified social movements that have been translated into political actions and regulations as main drivers for Germany's energy transition. These movements have set an economic environment and have defined requirements as well as demands towards the pillar of technology. Energy companies must observe their regulatory and social environments and the stakeholders' will in order to avoid missing substantial transformations. An enhanced agility of the major utilities is necessary for that. The cause-and-effect analysis shows that energy transition is a comprehensive process, which is driven by multiple factors, and that many stakeholders have significant impacts on these factors.

4.2 Research Paper 2

In RP2, the financial performances of different constellations of a private prosumer are determined with a self-developed TCO_P model. The data obtained in this way regarding the financial effects of different investment decisions make it possible to derive a wide range of insights.

The findings provide some clear guidelines for potential investors: Regardless of the size of the household, a PV system of any size will always create a positive financial added value compared to being solely a consumer. Nevertheless, the larger the system, the more advantageous it is for the owner.

A 4-person household can reduce its annual financial burden by approx. 500 € or 37% with a 9.76 kW_p PV system. With a 4.88 kW_p PV system, it is already possible to save approx. 300 €, i.e. 22%, per year. For two people, the possible savings are around 380 € or 45% with a 9.76 kW_p PV system and around 200 € or 24% with an investment in a 4.88 kW_p PV system.

However, adding a battery storage system will not create a financial advantage in all scenarios considered. This outcome is different to the information that some suppliers provide to potential customers [95, 96]. For example, the calculations often include the full electricity price for self-consumption but neglect lost remunerations for fed-in electricity. This omission leads to too favourable economic results for additional storage capacity.

For a 4-person household, according to RP2, an investment in a BES with a capacity of 6 kWh leads to an annual additional burden of about 300 €, regardless of the chosen size of the PV system. Larger BESs increase the additional burden. For smaller households, the additional burden is even higher.

Even though the main focus of this paper is not the prosumer's self-sufficiency rate, it should be mentioned that the autarchy of the prosumer increases dramatically with the added BES.

The largest increase is experienced by a 1-person household with a 9.76 kW_p PV system. Here, the use of a 6 kWh BES increases the autarchy rate from 50.83% to 94.80%. A larger BES can further increase the autarchy rate (a 10 kWh BES in this case to 95.83%), but only slightly. A 4-person household with the same PV system can increase its autarchy rate from 45.64% to 76.93% with a 6 kWh BES. With a 10 kWh BES, 80.46% can still be achieved.

The low correlation of financial efficiency and the self-sufficient rate is based, on the one hand, on the fact that a battery storage system only creates financial added value in the amount of the difference between the costs for electricity from the grid and the remuneration for fed-in electricity. On the other hand, the amount of self-generated electricity which is stored for the prosumer's own subsequent use is relatively small and can hardly be increased by larger battery sizes. Thus, the high purchase prices for batteries cannot be justified from the prosumer's point of view. This result points to possibly misallocated incentives for the prosumer model.

If there is a political will to increase the number of privately installed BES, then it is clear that the incentives need to be reconsidered. With an increasing share of RES, storage systems will be increasingly needed to cover volatilities. Subsidies and remuneration systems for BES could be interlinked to the willingness of the owner to provide access to the storage system for stabilisation activities. With increasing numbers of smart charging options and a rising demand for electricity, local storage systems cannot only help to improve the self-sufficiency rate but also to help stabilise the grid.

In addition to the lack of a large-scale market structure for the prosumer model, some required equipment, such as a BES, is still expensive. In RP2 a wide range of possible scenarios are investigated which help to make the business model of a prosumer profitable, and critical aspects are identified that future market structures should consider if the investment by prosumers in BES systems is to become more attractive.

The results show that the assumed prices (to be paid by the prosumer) for BES have to be reduced to at least half in order for the operation not to lead to a financial burden.

The paper also shows that the required load for private prosumers is too small (depending on the size of the PV system). As already mentioned, political incentives could subsidize the installation of a BES system in a different way. Indeed, energy transition can proceed to the next step if an additional load, such as electric vehicles or combined heat pumps, is implemented into the system.

Another development which could increase the financial attractiveness of a BES is the use of so-called ancillary services. The storage capacities of numerous prosumers can be bundled by an aggregator who offers ancillary services for frequency and voltage control to system operators. Since these services are remunerated, there is the opportunity of extra payment without additional or only low-cost investment and, since services can potentially increase the efficiency of the energy system, it would be reasonable to create corresponding policy measures to support such a development.

4.3 Research Paper 3

In RP3, the investigation of the financial performance of the private prosumer from RP2 is continued and expanded to include the possibilities of sector coupling. The findings of the investigations are presented below.

Even when applying the concept of sector coupling, the use of a BES system does not become economically beneficial under the current conditions on the German market.

If the heating sector is included, it is interesting to note that for a 3-person household, regardless of whether they are heating with a gas heating system or with a heat pump, the investment in a 6 kWh BES results in an additional annual burden of approx. 300 €. Furthermore, linking the electricity sector with the heating sector by using a heat pump or a heating rod leads to financial disadvantages for the prosumer. For the 3-person household mentioned above, these disadvantages amount to about 400 € per year if a heat pump is used instead of gas heating.

Taking the charging of a BEV into consideration does not lead to any remarkable changes regarding the financial assessments.

Nevertheless, RP3 shows that the desired effects of increasing the levels of self-sufficiency and locally consumed energy by using a BES and heat pump can be achieved.

Considering only electricity, a 3-person household without BES with a heat pump achieves a self-sufficiency rate of 34.82% (with 6 kWh BES 52.88%); with gas heating it is 47.07% (with 6 kWh BES 82.46%). However, the self-sufficiency rate in relation to the total energy consumed is more relevant for a comparison. For the heat pump the values remain unchanged, but the combination with a gas heating system only achieves 8.48% (with 6 kWh BES 14.85%). These values show the potential that lies in the private prosumer with sector coupling. Without the high investment costs, the increased self-sufficiency rates would also result in financial benefits.

Nevertheless, the financial gains stemming from the use of a BES system or heat pumps are not sufficient to pay for the high initial costs, even under a long period under review. However, we have also illustrated how future developments may make the use of BES beneficial to prosumers from a financial point of view. The effects of decreased BES prices are obvious, but a reduction in feed-in tariffs could also drastically change the economic situation.

The calculations of RP3 show that the use of a heat pump and a BES reduce the CO_2 pollution during operation by more than 50% compared to the sole use of a gas heating system.

Based on this, the potential effects of CO_2 pricing are investigated. Although solely introducing a CO_2 price will hardly lead to the financial advantageousness of a BES system or a heat pump compared to gas heating, in combination with other measures and changes in the framework conditions, the economically preferable alternatives can change with the CO_2 price.

4.4 Research Paper 4

FP4 continues the study of the private prosumer by carrying out an ecological assessment after the previous economic assessment. Using the established procedure of LCA, the environmental impact of the prosumer is determined.

We found that in the GWP impact category a household can indeed reduce its environmental impact by using a PV system and a BES. While previous studies which examined the financial benefits of these assets only assessed the PV system positively, our study also attributed added value to the use of the BES in terms of the GWP. However, this added value contrasts with a significant increase in the impact categories ODP and HTP, particularly caused by the BES. In the area of TAP, the most advantageous constellations with regard to GWP lead to similar results as those for the conventional grid supply.

Different implications can be derived from our results. For political decision-makers it is relevant that private prosumers with PV systems and BES contribute to the climate protection goals. In this respect, government support may be justified. However, the contribution is "bought" by increased environmental impacts in other categories that are partially dependent on the changing electricity mix from the public grid. At this point, it is recommended to strike a balance between the extent of greenhouse gas emission reduction and the additional burden posed by other factors, considering the way in which this all relates to other climate protection measures.

The outcome is similar for private decision-makers. The motivation of many prosumers to increase the self-consumption rate by using a BES in order to create an ecological added value, even if this does not pay off financially, is justified in terms of the GWP. However, the growing impacts in other categories should be taken into account, as the exclusive consideration of greenhouse gas emissions is too one-sided.

5 Conclusion

5.1 Summary and Interplay Between the Individual Research Papers

The energy sector, and the electricity market in particular, are strongly shaped by regulations. These regulations are set politically, but this process is and has been (increasingly) shaped by environmental aspects and societal will. In addition to the fundamentally secure supply of electricity to industry and to the population at all times, the central goal is to reduce environmental pollution, especially pollution from emitted greenhouse gases. International and national target values are derived from these goals, leading to the implementation of individual regulations, promotional measures, etc.

One model that is specifically promoted (in Germany) and protected by regulations is the private prosumer. It was shown that the operation of a PV system is always financially advantageous for the prosumer, and a large system should always be chosen. This result will not change even if feed-in tariffs continue to fall. This strategy is also advantageous from an environmental perspective.

The second asset of the prosumer, the BES, is more critical. In the basic concept with PV and BES, no constellation could be found in which the use of a BES is financially advantageous regardless of its capacity. In the related investigations, it was found that nothing could be changed by applying the principle of sector coupling. The CAPEX of sector coupling assets remains too high to be offset by savings during the use phase. Large reductions in acquisition costs would be necessary to change this situation.

However, the considerable effects of BES on the self-sufficiency rate and the self-consumption rate of the prosumer should not be underestimated. If a private decision maker is primarily concerned with these values, the use of BES on the basis of the results presented here can be fully endorsed.

In the extension of the private prosumer through sector coupling, the introduction of a heat pump is noteworthy. From a purely financial perspective, its use does not lead to any benefits; however, the effects on the self-consumption rate and on the self-sufficiency rate in relation to the total energy consumption (electricity and heat) are significant. The heat pump also has a correspondingly positive effect on environmental performance.

The ratios in the assessment of environmental impacts are correspondingly high. A BES can lead to a (significant) improvement in greenhouse gas emissions, even when its entire life cycle is taken into account. However, the negative side effects of other environmental impact categories should not be neglected.

5.2 Theoretical and Practical Implications

Theoretical

Regulations do not just appear or happen. Nor does the best idea simply prevail; the regulation process is a complex one. Regulations must be critically examined to determine the extent to which they actually contribute to their implied goals. It is therefore important to (also) examine this consideration from the perspective of the “user” or the “affected party”.

There is still a need to scientifically accompany technical and regulatory developments in Germany’s energy transition. Modelling must be adapted or newly undertaken, as the often-complex interrelationships, even in the case of initially simple issues, can only be mapped with sufficient precision by using scientific approaches. Simplified approaches to evaluation usually do not meet these requirements and/or are interest-driven. Science as a neutral observer is, and will remain, crucial.

For example, BES providers disregard any adverse aspects and provide one-sided calculations on the financial benefits of using their products. In the same way, political decision-making processes are often guided by individual interests and therefore need to be accompanied by neutral, fact-based studies. The example here is the shift in mobility away from fossil fuels, where electrification in combination with battery storage has been quite one-sidedly pushed (in terms of subsidy policy).

In future studies, it will be indispensable to consider the CO_2 price and the effects of different development scenarios on the results. In this way, the effectiveness of this instrument can be assessed and a realistic picture of the "hidden" potentials of individual technologies can be drawn.

The energy transition must continue to be critically accompanied at all steps in order to evaluate those steps that have already been taken and to recommend future directions.

Practical

For the private decision-maker, one implication is clear: operating a PV system is beneficial. This applies both from a financial perspective and from an environmental perspective. Even if the remuneration changes in the future, this recommendation can be maintained. The assessment for the operation of a BES must be more differentiated. Financially, BES is not worthwhile for the private prosumer, even with the application of sector coupling. However, for a decision-maker who primarily wants to achieve a high self-sufficiency rate and has an interest in contributing to climate protection, BES is clearly worthwhile. However, the isolated negative environmental impacts of BES should not be forgotten. The same applies to sector coupling by means of a heat pump. Even if the financial benefits are not (yet) there, great advantages can be achieved in terms of the self-sufficiency rate and thus local energy production and consumption.

From regulatory and political perspectives, the question of a suitable strategy for the development of storage solutions is also central. Here, it must be considered whether the central solution is desired by the private prosumers. If it is, the subsidies and/or pricing must be decisively changed. Due to the partial environmental disadvantages, centralised solutions at the local level should possibly be strived for, which can be designed more sensibly both economically and ecologically. Such solutions would also have to be introduced in combination with an appropriate framework.

5.3 Limitations and Further Research

The focus of the studies underlying this dissertation is on the individual private prosumer. With an increasing share of private prosumers, it will also become increasingly important to study the interplay of prosumers with each other and their united influence on the grid. The merging of individual prosumers into larger units must also be considered. This action could result in further opportunities arising with regard to electricity exchange among each other and active participation in the electricity market. The provision of ancillary services could also become an option and could expand the financial possibilities.

In the present studies on prosumers, simulations were carried out with real-world data, an approach which represents a clear progress over previous studies. Nevertheless, the results were determined on the basis of average values. Field studies could be used to identify different types of users. For different user groups, the answers to the investigated questions could possibly turn out slightly differently.

Otherwise, the studies presented here need to be adapted to the constantly changing framework conditions, and they can be used to examine the effectiveness of future changes in regulations and subsidies.

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Part 2: Research Papers

1 Research Paper 1 – Causes and Effects of the German Energy Transition in the Context of Environmental, Societal, Political, Technological, and Economic Developments

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Abstract

Background

As lignite mining protests and #FridaysForFuture demonstrations gain momentum in Germany, this paper investigates the various causes and effects of the country's energy transition. Society and politics alongside economic, environmental, and technological developments have led to a profound and continuous transformation of the energy system, a transformation which is remarkable in terms of reach and speed for an economy the size of Germany's. Pressure to transform the country's entire energy system even faster has recently been levelled due to the Russian invasion of Ukraine.

Results

From the perspective of the different pillars of sustainability and various stakeholder groups, this paper discusses the influences and their interdependencies towards the status quo of the German energy sector. We have used the cause-and-effect analysis method to answer the question of why major energy generators in Germany are still struggling with the energy transition, as well as the question of why a strategy towards more sustainability is needed to maintain Germany's industrial strength in the long run. We found that energy transition in Germany is substantially driven by society, which pushes political decisions that lead to an economic transition, while environmental incidents are only triggers for further societal and political doings. Furthermore, technological developments fulfil only needs and do not necessarily hurry ahead of time.

Conclusion

Overall, the article creates a profound understanding of the factors influencing the German energy transition which is deeply embedded in the European energy system.

Keywords

Sustainability, Renewable Energy, CSR, Energy Transition, Cause-and-Effect Analysis

1.1 Introduction

The long-term development of the transition of the German energy system is of utmost importance for Europe, as Germany has not only the largest economy on the continent. In addition, the various influencing factors identified in this paper and their interplay provide examples of how energy systems change in the long term and how companies can adapt to them at an early stage. These developments are important not only because of Germany's integration into the pan-European energy system, but also because Germany is a key political actor in the European Union and plays a decisive role in determining which trajectories are chosen in response to past, present, and future political events such as Russia's current invasion of Ukraine. A deep understanding of the German energy transition can therefore help to better assess current and future developments and the associated technological, ecological, economic and social consequences in other countries and the European Union as a whole.

Germany is internationally considered to be a pioneer in the transition of its energy system towards an increasing share of renewable energy sources [1–3]. Years ago, the then chancellor, Angela Merkel, was actually regarded as the "climate chancellor" [4]. Today, however, Germany has fallen somewhat behind by international standards. In 2020, the target of a 40% reduction in GHG emissions compared to 1990 was only just achieved, and that was due to the consequences of the Covid-19 crisis. The achievement of the targeted 55% reduction by 2030 is so far uncertain [5].

In Germany, currently 489 g of CO_2 are emitted during the generation of one kWh of electrical energy and, hence, a way has to be found to decrease carbon emissions and to further accelerate the transition of the energy system [6]. To promote the transition, the regulatory framework has been changed towards a market system favouring multiple and decentral players besides the large energy-generating and network-operating companies. Nevertheless, the electricity price in Germany is one of the most expensive in Europe, even though the market system has been liberalized by law [7]. In this context, Germany has made intense efforts to change its methods of generating electricity in the last decades. In summary, however, it can be stated that Germany is not the leading country in terms of the overall share of renewable energies in total energy consumption by international comparison, but is, at best, average [8].

The energy sector is strongly regulated and of central importance, and it is essential to consider the interactions between the economy, politics, and society and to include these in decision-making processes in order to be able to act successfully in the long term. As an important basis for the prosperity and functioning of an industrial nation, the sector of electrical energy generation is highly relevant for many stakeholder groups.

This paper summarizes the most important events and decisions of recent decades that have influenced the transition of the German energy system. The factors are grouped into categories and analysed according to their cause-and-effect-relationships. Their interdependence is analysed in an Ishikawa Diagram (cause-and-effect diagram). In addition, the opportunities and risks as well as the obstacles, including the relevant path dependencies of the energy transition, are considered from different angles. The implementation of some of the possible solutions is being hampered by society and by politics; others are not yet technologically feasible and need further research and development. To sharpen these perspectives, we need to consider them separately at first, to merge them, and to set them into context with each other. This can help to identify what would be the best way to continue with the transition of the energy system, to understand why, for instance, large German energy producers are struggling with their business models, and to determine how to overcome dependencies on critical suppliers, e.g., those located in Russia or the Middle East.

The influences on the energy sector are manifold and can be attributed to society, politics, the economy, the environment, and technology. Their interdependencies are not obvious at first glance. This paper analyses dependencies and interdependencies and also reflects that not every approach to sustainability or Corporate Social Responsibility (CSR) is measurable or even yields a positive economic output. However, to overcome economic disincentives, politics can provide incentives to induce desired changes. On the other hand, private and corporate consumers can exert great influence on the energy sector by making decisions that modify their consumption patterns and by actively participating in social movements and influencing politics. The associated developments also point towards approaches for the future progress of the energy system transformation. At the same time, the energy system has an enormous inertia that makes it difficult to implement new business models and to establish new supply channels. For companies, an understanding of their environment that considers all stakeholders is fundamentally indispensable. This applies to the energy sector in particular, considering the boundary conditions described above. In order to gain this understanding and to derive arguments for future developments, we examine the following research question:

1st Research Question

What effects have played a substantial role in the German energy transition and how have they interacted?

In the energy sector, various political and economic regulations impact electric utilities and other companies. Thus, we have studied the effects of these regulations in the on-going process of the energy system transition, and how these regulations have changed over time. Specifically, we investigate the question:

2nd Research Question

What regulations have influenced companies in the energy sector during the German energy transition?

1.2 Research Method and Baseline Approach

The transition of the German energy system (Deutsche Energiewende) is one example of disruptive changes that are turning the energy sector into a more sustainable industry. On their path to generating electricity with fewer or even no carbon emissions, the European states have chosen different approaches. For instance, France relies on nuclear power in a centralized grid [9]. Denmark already has almost 100% Renewable Energy Systems (RES) in a decentralized grid [10]. Germany can be found between these two extremes. On the one hand, the German government is subsidizing decentralized renewable energy production, such as Photovoltaics (PV) or wind turbines. On the other hand, the German government also subsidized coal mining in the Ruhr area over a long period, which is mainly used for generating electricity in large coal and lignite power plants with massive CO_2 emissions.

Lately, huge protests against lignite mining and coal-fired power plants have attracted up to 50,000 people to one protest march alone [11, 12]. As a result, the national government has established the so-called Coal Commission (Kohlekommission), which has developed a plan and a timeframe to shut down all coal- and lignite-based power plants. Representatives in the Coal Commission are from different stakeholder groups who are to reach a compromise on the future of coal usage in Germany's energy sector [13].

These examples of different European states illustrate how different stakeholder groups and their interactions can lead to different assessments of and solutions for the same problem. In our paper, we show the need to take a holistic view of the process of energy transition due to the numerous actions and dependencies among the stakeholders involved [14].

1.2.1 The Three Pillars of Sustainability and Technological Improvements

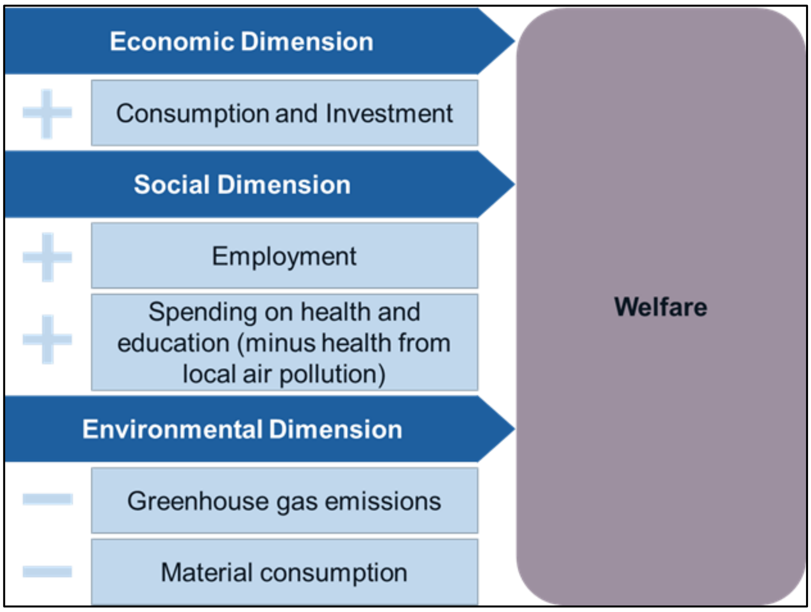

Figure 7: Dimensions of Sustainability (see [14])

Aim, Design and Setting of the Study

Sustainability is, per definition, an integrated concept, which comprises different perspectives [15]. Most of the literature refers to the three-pillar concept which includes the economic (consumption and investment in productive capital), the social (including human capital improvements through healthcare and education), and the environmental (including the depletion of natural resources through consumption of materials) dimensions [14]. These three pillars are accompanied by political influences, since the supply of energy-relevant resources is playing an increasingly political role, e.g., in political conflicts such as the recent invasion of Ukraine by Russia. The three-pillar concept, including the political dimension, is summarized in Figure 7.

This paper creates a detailed understanding of the factors underlying the transition of the German energy system as seen from the different perspectives of sustainability. Based on the three pillars of sustainability, it visualizes the various impacts which have led to the status quo.It also provides an overview of the changing market structures and challenges that electricity generating companies are having face during current phases and will have to face during future phases of this transition.

Customers, grid management, but also entire sectors are affected by the change towards more sustainable industries. Since the stakeholders of sustainable energy supply are numerous and the energy sector is particularly connected to politics, the necessary ground-breaking changes need to be promoted and deployed without jeopardizing the successful operation of the energy system and major industries. Hence, sustainability and CSR are not only a relevant topics for electricity generation and supply but also an important issue for the entire economy [16].

The benefits of the energy transition cannot, therefore, be measured only with traditional indicators, such as cost and revenues. It is not yet possible to clearly state whether and how costs can be saved by avoiding CO_2 emissions. There will also be tremendous impacts on the environmental and social performance of the reformed energy sector [14]. In the following we characterize four relevant pillars from the perspective of the main stakeholder or representative. In addition to the three pillars of the sustainability concept, we consider the specific role of technology as a fourth pillar. Technological improvements not only enable the transition of the energy system; they also add to the complexity and enable different paths towards more sustainability. At the same time, technological development creates new path dependencies that will be relevant for the design choice in the years to come. In addition, we consider political developments in the societal pillar that are not the outcome of societal claims for more sustainability but that reflect rather the political conflicts between countries, groups of countries, or regions. In this vein, resource supply is used as a weapon to enforce political interests which are only loosely connected to the energy sector. For this reason, this study adds "technological improvements" to the three existing dimensions [17–19].

Economic Perspective

The German energy market has been traditionally dominated by four large energy supply companies (E.ON, EnBW, Vattenfall, and RWE). Precisely these companies have faced considerable challenges due to the deregulation of the electricity market and the changes in the energy mix associated with the transition of the country's energy system. When the energy suppliers were confronted with the economic consequences of these challenges, a large wave of restructuring in the energy market began, which led to – among other aspects – companies being split up, as well as to mergers and acquisitions. Simultaneously, the transition of the energy system has led to the need for new, decentralized solutions, particularly in the areas of smart energy distribution, storage solutions, and grid security. [20]. Consequently, new companies were also able to establish themselves in these business areas. These developments have significantly weakened the traditionally oligopolistic structure of the energy market.

The Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) has had an enormous impact on the development of the electricity market, as PV systems have been specifically promoted and subsidized as private investments. These subsidies have substantially changed the energy mix of electricity generation in Germany and are seen as an important prerequisite of the transition of the country's energy system.

For the four big electricity suppliers mentioned above, this development has had several effects. First, the Merit Order Effect has cut the prices for energy. Second, on windy or sunny days, the capacities of conventional fossil fuel-based power plants are no longer needed, whereas these capacities are still required on days when electricity generation from renewable sources is low. These changes in demand have had severe consequences for the economic profitability of Germany's conventional power plants, although Yinab and Duan (2022) have shown for China, that coal-fired power plants can support the transition towards a renewable energy system economically efficient [21]. Third, the weather-dependent and volatile generation of renewable energy needs to be backed up by conventional power plants in order to ensure grid stability. In the future, storage solutions can be expected to significantly mitigate this problem. Overall, the changed market structure together with the restructuring of the four largest energy suppliers has formed one of the key premises for the transition of the German sector towards the use of more renewable energy sources.

Environmental Consequences

The environmental pillar comprises the impact of human activities on the natural environment as a source (supply of raw materials) and as a sink (absorption of pollutants). These activities are having dramatic effects on the functioning of the earth's ecosystems, which are apparent, for example, in the destruction of entire landscapes, in climate change, and in a dramatic decline of biodiversity. The ongoing climate change in particular has been an important impetus for rethinking traditional forms of energy production and use [22]. Since the corresponding negative environmental impacts materialize as external effects and thus do not (fully) underly market mechanisms, policy-makers have increasingly regulated energy systems in line with many stakeholders and have created economic incentives to reduce negative environmental impacts [23–25].

Society and Politics

The social pillar of the sustainability concept addresses the effects of regulatory and economic systems on the living environments of people. This includes aspects such as fair income distribution, social cushioning of disadvantaged individuals and groups, education, compliance with human rights, equal opportunities, and gender justice. Hence, the energy justice in the transition of the energy system plays an important role, locally and globally [26]. Regarding the energy system, security of supply and a socially acceptable price levels are of particular importance [27, 28].

Social systems are influenced in particular by the institutional framework of a society and the voting behavior of the population, but also by political movements, single events – such as Fukushima – and also media coverage. This repeatedly leads to changes in the attitudes of politicians, the population, and decision-makers over time [29]. Some changes in the mindset are at first just represented by a minority and grow over time, some changes are obvious, and some changes are only latent and must therefore be stimulated. Political movements, newly founded NGOs, or even new political parties are the consequence of these changes [30]. However, society and politics in Western Europe are usually linked to each other. Big changes within a society affect the decisions made by policy-makers, who operate within a given institutional framework [31]. In this paper, the third pillar covers not only society and societal movements, but also political decisions and the political framework in a regulated energy market.

Technological Improvements

Since energy transition is also a question of technological feasibility, we introduce a fourth pillar in addition to the three established pillars of sustainability and refer to it as “technological improvements”. Hardly any of the past and current changes made to the energy system would have been possible without the corresponding technological changes. These include changes being made in the generation and distribution of electricity, and technological progress taking place in wind energy, photovoltaics, and hydrogen production. Improved information and communication technologies, which allow improved grid management, can also be mentioned here. Specifically, a higher share of decentralized generation of electricity without mechanical inertia creates the need for redundancies and storage as well as a better coordination of the grid. Research and development to improve existing technologies or to create new ones will continue to be a key factor for the success of energy system transformation in the future. For example, smart technologies are increasingly being used for grid control, and more powerful storage technologies are needed to balance the grid. Technological developments, particularly in information and communication technologies, also make it possible to link sectors that were previously operated separately, such as the energy and mobility sectors.

1.2.2 Cause-and-Effect Analysis

The cause-and-effect analysis is a tool which describes relationships between causes and their effects. Originally, the cause-and-effect diagram was invented and developed by Kaoru Ishikawa as a tool for quality management. Therefore, it is also called the Ishikawa diagram [32].

Characteristics of the method

An Ishikawa diagram usually has the following structure: The core problem to be considered is positioned at the top. Subsequently, the main factors influencing the problem to be investigated are identified and installed as branches along a main axis. The resulting construct resembles the skeleton of a fish, which is why the diagram is also called a “fishbone diagram”. In a second step, the main influencing factors are assigned to subcategories

which branch off from the large bones as small bones [33]. Thus, an Ishikawa diagram can be used to present the search for and the development of the causes of a problem in a structured and detailed way [32, 34]. Over the course of time, the Ishikawa diagram has also been adopted by other disciplines to explain complex and multi-causal relationships. The use of this method in various research areas shows the versatile possibilities of applying the Ishikawa diagram [34–37].

Description and limitation of the method

Hence, Ishikawa diagrams are also suitable for explaining complex developments, such as those that have led to the transition of the German energy system. Even though the distinction between causes and effects is not always clear, the diagram can show how interdependencies between different factors have affected actions and reactions of multiple stakeholder groups and how these interdependencies have fostered developments in the three different sustainability perspectives as well as technological developments. As all of the four perspectives have contributed to the energy transition in Germany within the last decades, they will be analysed separately first and then combined in an overall Ishikawa diagram. This approach facilitates not only a better understanding of the transition of the energy system in Germany but also provides the opportunity to draw conclusions on future trends and on developments in other countries.

In this paper we use the terms of “pillars” and “perspective” for the three sustainability pillars and the perspective of technological developments respectively. These are influenced by different categories which sum up events or influencing factors (see Figure 8).

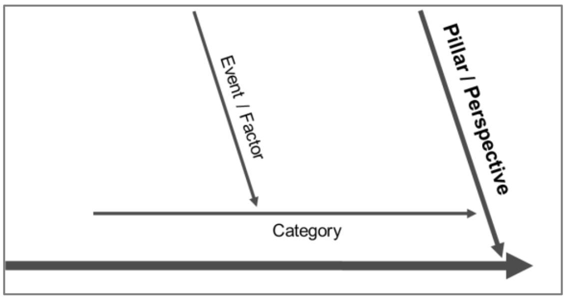

Figure 8: Nomenclature of the Diagram in This Paper

1.3 Perspectives of the Energy Transition in Germany

For this study, we searched for all events which concern German politics regarding energy and especially electricity, the transition of the German energy system, and the German regulations regarding electricity generation and distribution from a historical, social, and political point of view. For this purpose, we considered all events which have affected at least one of the perspectives. For each of these perspectives (economy, environment, society, and technological improvements), we identified the factual basis and depicted the identified relationships.

Following the creation of the Federal Republic of Germany in 1949, energy policy was initially seen exclusively as a necessity for the economic development of the country. While concentrated primarily on power generation from hard coal and lignite, the main focus after World War II was on restoring the grid infrastructure and securing the reliability of the electricity supply [38]. After a period of economic and social upswing, and triggered by new ground-breaking scientific findings, Germany society – alongside emerging political movements – began to question the country's behavior in terms of sustainability. A prominent example is the Club of Rome, which was founded in 1968 [39] and published its first report "The Limits to Growth" in 1972 [40]. This report indicated the problem of population and economic growth that would exhaust the resources of planet Earth within one hundred years. As a consequence, the report stated that economic and policy systems needed to be redesigned towards a higher focus on sustainability. However, this report was only one important factor over the course of time. In the period analysed in this paper, we consider the timeline from World War II to today and divide this period up into the following distinct phases:

(1) From World War II to 1968 (foundation of the Club of Rome)
(2) From 1968 to the 1986 Chernobyl accident
(3) From the Chernobyl accident to the 2011 Fukushima accident
(4) From the Fukushima accident to the present day
(5) The Russian invasion of Ukraine

1.3.1 Timeline of Relevant Factors

The cause-and-effect diagram enables the visualization of the type and numbers of categories that are relevant for the different perspectives. Although this approach cannot replace a sound evaluation of every event, the Ishikawa diagram does illustrate relevant relationships in a clear way. Figure 9 summarizes the relevant events and influence factors for the economic perspective.

Economy

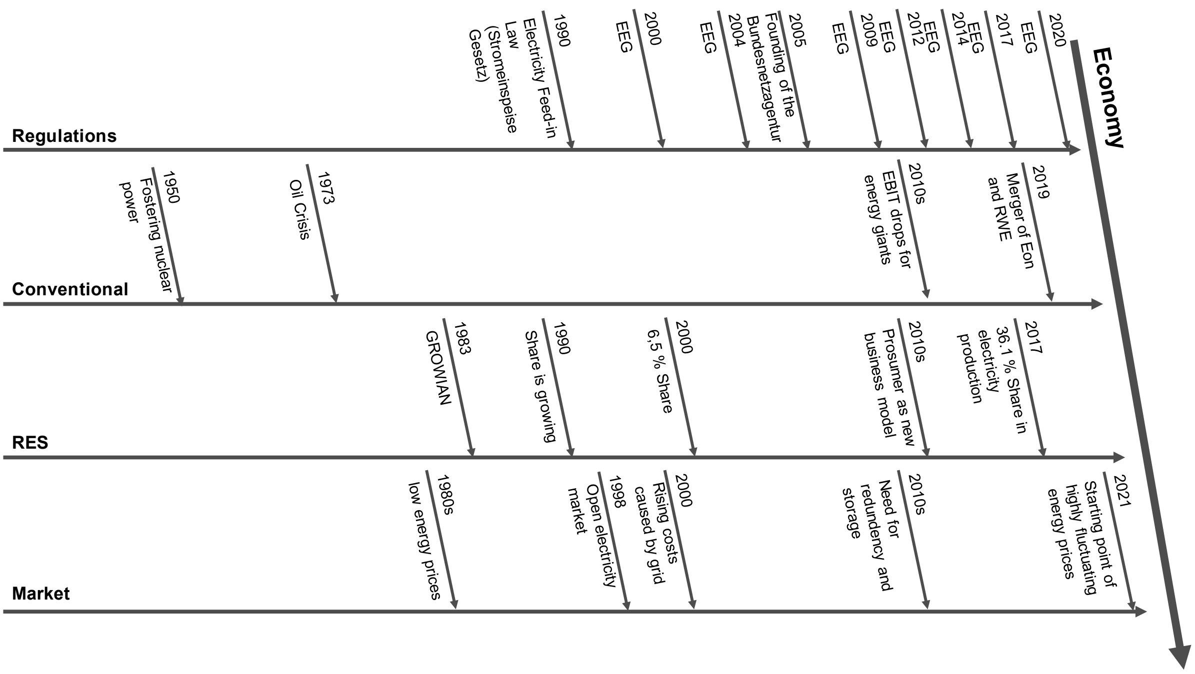

Figure 9: Economic Factors

For the economy pillar, we distinguish between two types of energy generation (conventional and renewable). Furthermore, we reflect regulatory changes that are relevant for the market structure as well as market developments, such as external shocks and regulatory implications, which have led to changes in revenue and cost structures.

(1) From WWII to 1968, Germany relied on energy generated by coal and lignite, with these resources being mined by large montane corporations, which employed a substantial number of people [41] and required large and cost-intensive assets to be utilized over several decades [42–44]. During the time of Germany's "Wirtschaftswunder" (the Economic Miracle) the economy demanded more and more cheap energy, which ultimately led to high emission levels and severe environmental problems [45–47].

(2) From 1968 to the Chernobyl accident of 1986, a few decades of massive use of fossil energy sources passed. In 1973, the first oil price crisis hit the German energy sector, resulting in higher

energy costs for companies and private households. In order to cushion the dependence on external market shocks and any accompanying economic crisis, politicians increasingly focused on nuclear power [39]. While industry and politics were able to stabilize the energy production, the price levels for energy in Germany decreased [48]. Finally, in the early 1980s, the price levels for energy in Germany decreased [49], with an energy sector in place that was dominated by a few large companies running large fossil or nuclear power plants and supplying energy via a centralized grid.

(3) From the Chernobyl accident to the Fukushima accident in 2011, the economic conditions underwent radical shifts that were mainly driven by regulatory changes. Since 1990 the share of renewable energy production had been growing continuously. One reason for this was the Electricity Feed Act (Stromeinspeisegesetz), which was introduced in 1990 and fostered by the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, (EEG) in 2000 [50, 51], and which guaranteed high feed-in remuneration for energy from photovoltaic, wind, and other renewable sources. From the consumer's point of view, 1998 was a turning point, as the electricity market was opened up, weakening the oligopolistic structures. This so-called liberalization of the German electricity market allowed customers to freely choose their supplier of electrical power. With this change in policy, the government targeted high energy prices and market inefficiency. As a consequence, the energy prices dropped for just a short period before returning to their levels prior to liberalization [52], with the oligopolists being able to maintain their dominant market positions. In 2001, only ten electricity suppliers held a market share of 80%. During the period following liberalization, the market share of even the biggest electricity supplier in Germany did not change more than 2% over time [53]. However, liberalization did change the price-building mechanisms. The electricity price was now formed at the electricity exchange in a market-oriented manner. For this purpose, each power plant operator submitted a bid for a certain amount of electricity at a certain price. The offered "quantity" of the electricity depended on the installed capacity of the respective power station. The price was based on the marginal costs incurred by the type of power plant concerned. The price of the (marginally) most expensive power capacity consumed was the market price at which the electricity was traded. Thus, most power stations that offered a lower cost-based price were able to sell at a price above cost-based price levels [54]. This effect was mitigated by the first Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG) from 2000. The EEG not only guaranteed the feed-in of renewable energy, but also a fixed remuneration per kilowatt hour. The gap between the guaranteed feed-in remuneration and the market price was compensated by the EEG-levy [55]. The impact of the EEG act and the resulting pricing

structure for electricity and the profitability of conventional power plants were wide-ranging. The available capacities of the renewable energy sources were excluded from the inclusion in the Merit Order. As a result, the demand for traditional production capacities – which was the base for determining the prices – fell, taking into account the provided output of renewable energy generators. Consequently, the intersection of the remaining demand and supply curve shifted towards lower prices, at least when a substantial amount of solar and energy power was fed into the net. This had two consequences. On the one hand, the capacities of the expensive peak-load power plants (especially oil and gas power plants) could be used less frequently. On the other hand, the range between price and marginal costs also fell for power plants that were still in use, which led to particularly dramatic economic losses for power generators [54, 56]. As a consequence, the share of renewable energy has not only grown disproportionately since 2004 but also the profitability of the large electricity providers suffered substantially.

<u>(4) From the Fukushima accident to the present day</u>, the German energy transition has gained a tremendous momentum. The market fields have been newly divided and new regulations, including the obligatory phase-out of all nuclear power plants, have been introduced. The impact has been noticeable along the entire value chain [20]. Especially traditional electricity generators have struggled with the new regulations. Conventional power plants are no longer able to operate economically [57]. The EBITA of E.ON, one of the four largest electricity producers in Germany, decreased by 2.5 billion Euro from 13.3 billion Euro in 2010 to 10.8 billion Euro in 2012 [58]. Similar changes can also be observed in the other three large energy suppliers [59, 60]. Although the principle of "grandfathering", with a discount of 1.25 percent, was extended to the second EI Emissions Trading System period from 2008 to 2012, this did not help to improve the EBITA of the major energy producers [61]. One reason for that can be seen in the rising share of small-scale units for renewable energy generation, as Figure 10 [62] shows. The share of renewably generated electricity from wind, biomass, solar, and water increased from 23% in 2011 to 34% in 2015 and to 46% in 2019.

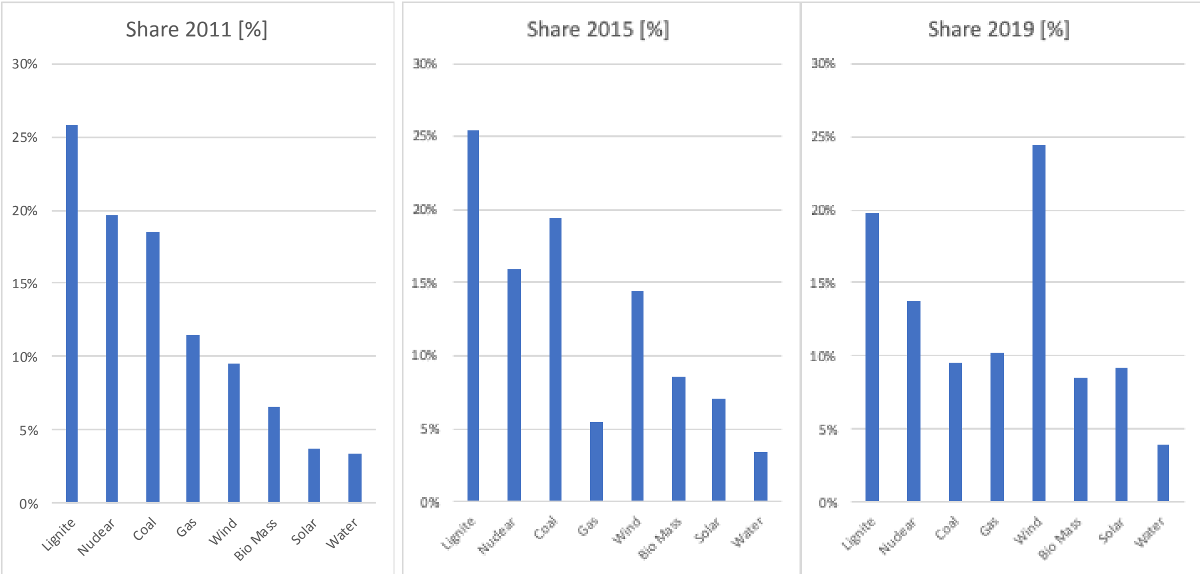

Figure 10: Share of Electricity Generation in 2011, 2015, and 2019

Furthermore, the prices on the electricity market have decreased due to subsidies and regulation, but also because the variable (marginal) costs of renewably generated electricity are lower than variable costs for conventionally generated electricity. Because of the Merit Order principle, the margins of the large fossil-based power plants have now increased dramatically. Figure 11 shows the average price per year of MWh electricity on the energy stock exchange in Leipzig [63].

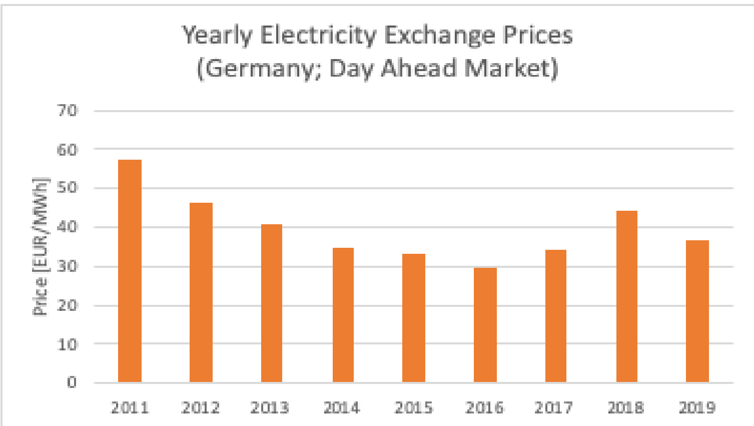

Figure 11: Average Price per MWh on EEX

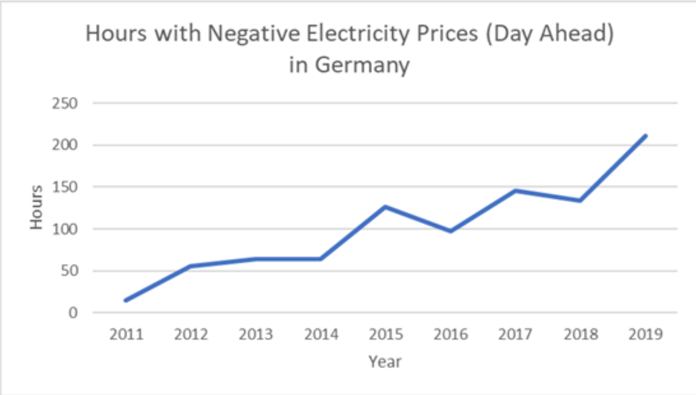

Figure 12: Hours with Negative Electricity Prices per Year in Germany

Additionally, due to the (weather-related) volatility of renewable energy generation units, the price for electricity can be negative at times of high peaks of generation. For large and inflexible power plants, this can be a problem, because of their continuous power generation. With a rising share of renewable generation, the volatility of generation has increased and, thus, the trend for hours with negative electricity prices has become more pronounced over time (see Figure 12). Due to these changes, and as renewably generated electricity has been supported by the EEG and direct subsidies, running a fossil-based power plant has become less profitable because initial investment costs have become more difficult to amortize.

Even though the energy transition requires high flexibility, which creates problems for large companies with large assets, overall, the German Energiewende has created many economic and non-economic opportunities. Next to objective consequences, such as creating new industries or business models, there are positive side-effects for wealth [64]. For example, the customer-centric energy supply system enables the creation of additional financial value for the owners of renewable power plants, such as rooftop PV systems. In addition, the avoided costs for environmental damage caused by emissions outweigh the costs for energy transition [65]. In this vein, the energy transition process has also stimulated a transition of the energy supply system which includes the formation of energy communities and the transformation of grid operators [66, 67]. For example, in 2018 two major energy generators and suppliers in Germany decided to merge their companies and to structure their business in a new way. Since competition is not driven between large energy providers anymore but small decentralized energy generators have started to dominate the market, RWE, with its newly founded subsidiary Innogy, and E.ON saw the need to bundle their energy generation sectors and separate them from their grid and supply operations [68]. These organizational restructurings reflect the market shifting from a traditional energy market towards service-based operations, which becomes even more visualized by the highly fluctuating energy prices since the end of 2021.

The electricity prices on the day ahead market started to increase and culminated in a mean price of 221.06 EUR per MWh in December 2021 [69]. One reason for this was the increased price for fossil energy carriers.

<u>(5) Russian invasion of Ukraine</u>

The energy price effect was levelled by the war between Russia and Ukraine. At the beginning of the war in February 2022, Germany was importing 50% [70] of its gas consumption from Russia, making it the world's largest consumer of Russian gas in absolute terms. 35% of the gas was used by industry; 15% went into electricity production [71]. EU-wide, 40% of the gas consumed was purchased from Russia [72]. In addition, Russia supplied 45% of Germany's oil imports [73].

While numerous economic sanctions were imposed against Russia after the beginning of Russia's invasion of Ukraine [74], a full embargo of the import of all fossil resources was not possible due to the great economic dependence in the energy sector. The energy market, which had previously been viewed primarily from an economic perspective, became all the more politicized. Among other things, the "Nord Stream 2" project, which had been pushed forward by Germany for a long time against resistance from the US and other EU states and was almost completed, was canceled [75]. The goal of reducing dependencies on politically less reliable partners came to the fore. Alongside the search for new supply options – such as liquid natural gas (LNG) – from overseas, the acceleration of the energy transition towards (regional) renewable energies also moved into the foreground of political discussions.

In summary, the transition of Germany’s energy system shifted the economic basis of the established energy sector towards a higher degree of decentralization, a shift which has challenged major electricity providers as well as grid operators. Hence, future electricity generation will be more volatile due to its dependence on renewable resources, such as sun radiation and wind, so there will also be a greater need for redundancy, storage, and smart electricity demand. It can be expected that recent political developments will accelerate the process towards electricity generation from renewable resources.

Environment

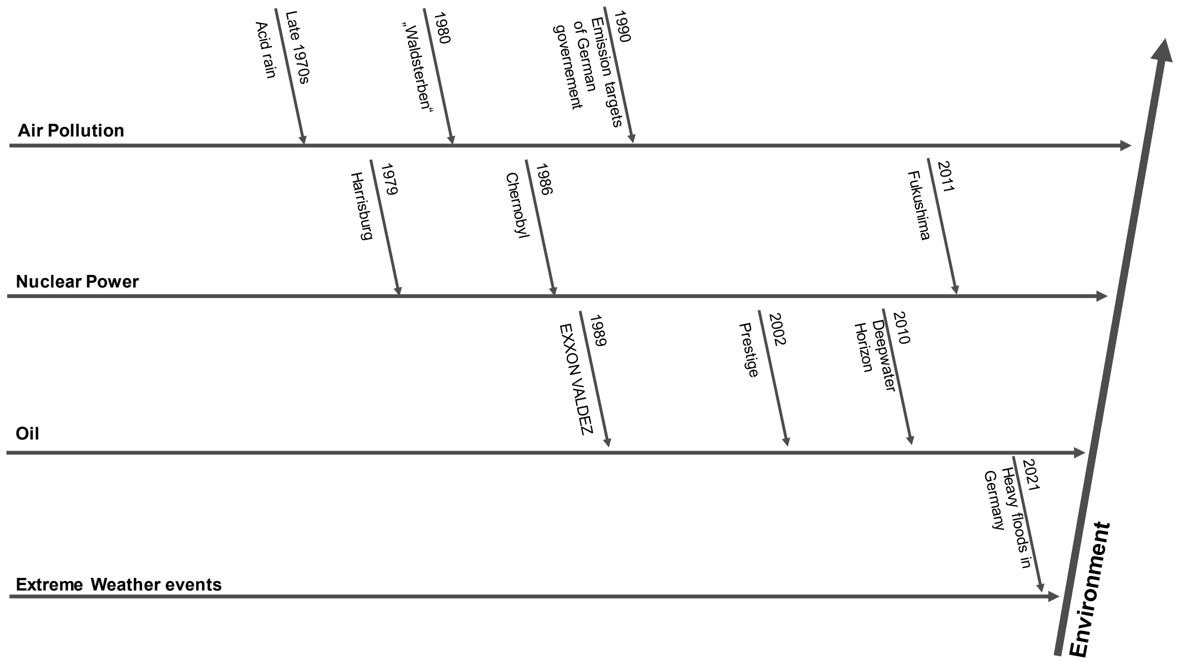

Figure 13: Environmental Factors

For the environmental pillar, we distinguish between three categories with the most global impact of the energy sector: air pollution due to burned fossil resources, nuclear accidents, and environmental catastrophes caused by oil.

<u>(1) From WWII to 1968</u>, the enormous use of coal and lignite caused a sharp increase of several types of emissions. Some areas in Germany, such as the Ruhr area, were extremely affected by exhausts from and the consequences of coal and lignite mining [45–47]. In his speech in connection with his candidacy for chancellor on April 28, 1961, Willy Brandt demanded that the sky over the Ruhr area should turn blue again [76]. On the one hand, the almost 100 coal-driven power plants were generating cheap electricity and heat, which was helpful for the heavy industry in that region. On the other hand every ton of pig iron was causing 8.6 kg of dust and the power plants were producing 4 million tons of sulfur dioxide every year [76]. This resulted in higher rates of leukemia and cancer, rickets and blood count changes in the core of the Ruhr area. Newborns in the Ruhr area were on average smaller and lighter than newborns in the Lower Rhine area [76].

<u>(2) From 1968 to the 1986 Chernobyl Accident</u>, nuclear technologies became more popular, but brought even bigger risks with them. The first large nuclear accident was the Three Mile Island accident near Harrisburg, USA, in 1979 [39]. It remains one of the biggest nuclear accidents to date [77, 78]. A closed valve almost led to a nuclear explosion because the fuel elements were melting and producing hydrogen within the power plant. About 2m people were

affected by the nuclear radiation [79]. In the late 1970s and early 1980s, Europe was facing another problem, which was a result of decades of emitting all kinds of exhaust gases into the environment: Acid rain and dying trees (Waldsterben) were challenging German's forests at this time [39]. On January 18, 1985, smog alarm level 3 of 3 was triggered for the first time [80]. Besides air pollution, a nuclear danger emerged with the Chernobyl accident in 1986.

<u>(3) From the Chernobyl accident to the Fukushima accident</u>, national politics in parts of Europe were taking a more critical view of nuclear energy. After nuclear radiation spread over Europe and forests remain partly affected until the present day, no new nuclear power plants were authorized in Germany [81, 82]. Only three years after the Chernobyl catastrophe, the Exxon Valdez oil tanker struck a reef off the coast of Alaska, contaminating 2,000 km of coastline. Up to 400,000 seabirds and 5,000 sea otters died as a consequence [83]. After these dramatic catastrophes with high media coverage, an awareness for the problem of global warming and better protection of the environment arose in German society and other European societies. Also, the 1990 Electricity Feed Act (Stromeinspeisegesetz) provides for the feed-in of electricity generated from renewable sources to be prioritized [50]. Furthermore, a Europe-wide directive was adopted in 1996 (96/62/EG), which obliged the member states to comply with certain air quality targets.

However, the occurrence of severe and environmentally harmful events did not stop. In 2002, the oil tanker "Prestige" lost 50,000 tons of oil due to a tank leak and 1,600 km of the Atlantic coastline in Spain, Portugal, and France were affected. Again several tens of thousands of seabirds died [84]. In 2010, eleven people were killed when the "Deepwater Horizon", an off-shore drilling rig, exploded and 780 million liters of oil contaminated the Gulf of Mexico and the coast of Florida [85]. The latest groundbreaking incident was the nuclear accident at Fukushima in March 2011, caused by the 2011 Tōhoku earthquake and subsequent tsunami. Three units were affected by meltdowns and more than 100,000 people had to leave the area around the power plant, in addition to the dramatic effects caused by the tsunami. Future consequences are still not fully predictable.

<u>(4) From the Fukushima accident until today</u>, no major environmental accident has taken place. Nevertheless, discussion about introducing fracking in Germany is ongoing [86] – the consequences of which for the ecosystem are not foreseeable – and energy generation in Germany is still dependent on fossil energy carriers. However, the levels of greenhouse gas emissions and the respective climate change remain a huge concern to the population.

Specifically, the flooding events in several areas of Germany in 2021 are often seen as a consequence of worsening climate problems [87].

(5) Russian invasion of Ukraine

Concrete effects of the war in Ukraine on the environment cannot yet be fully estimated. However, political decisions based on this event may have a positive environmental impact in the future. It is currently planned that Germany will terminate its coal and oil imports from Russia by 2023 and its gas imports by summer 2024 [72]. The war could act as an accelerator of the energy transition in Germany, as gaining independence from politically instable suppliers has become a political priority. In this vein, political and environmental interests can complement each other.

Summarizing the overview of environmental catastrophes, these accidents, no matter which category they belong to, appear randomly and cannot be predicted. Their influence on society and politics is analysed in the following section. In the case of air pollution, which is a more continuous event caused by exhausts, it can be seen that the elimination of the problem often requires years or decades. One reason for this is that technological, economic, and political changes must go hand in hand, as the further cause-and-effect analysis will show. Nonetheless, in recent years, overall emissions in Germany have decreased [88]. But Figure 14 also shows that, if a linear decrease is assumed, the trend of decreasing emissions during the last 30 years is too slow to reach zero emissions over the next 30 years up to 2050.

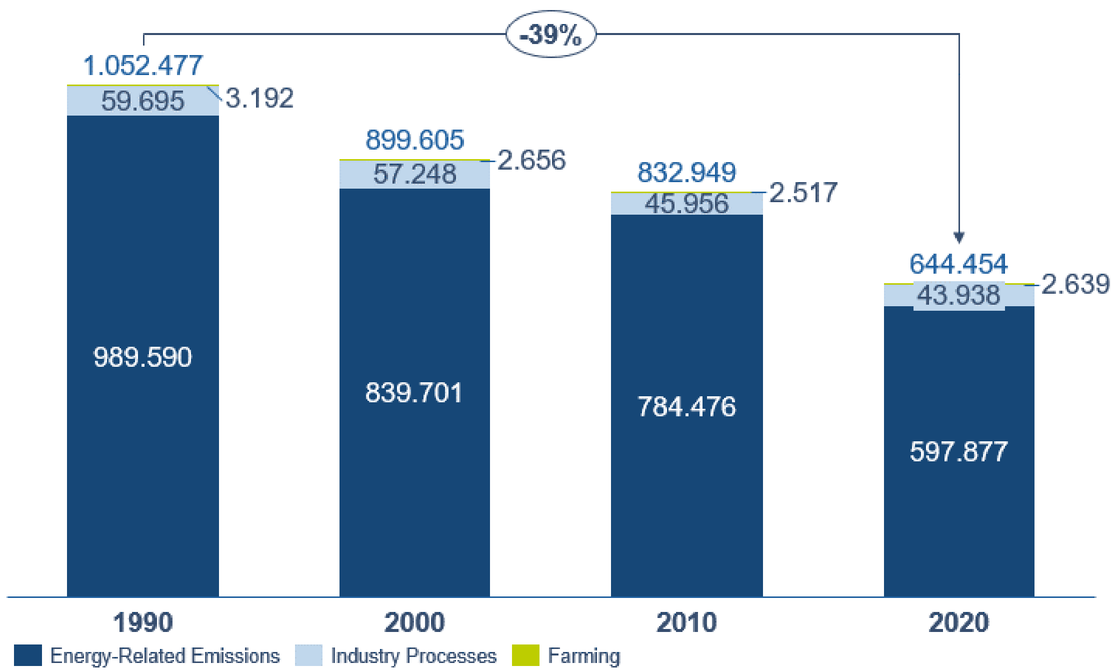

Figure 14: Emissions of CO_2 Equivalent in Germany from 1990 to 2020 [89]

Society and Politics

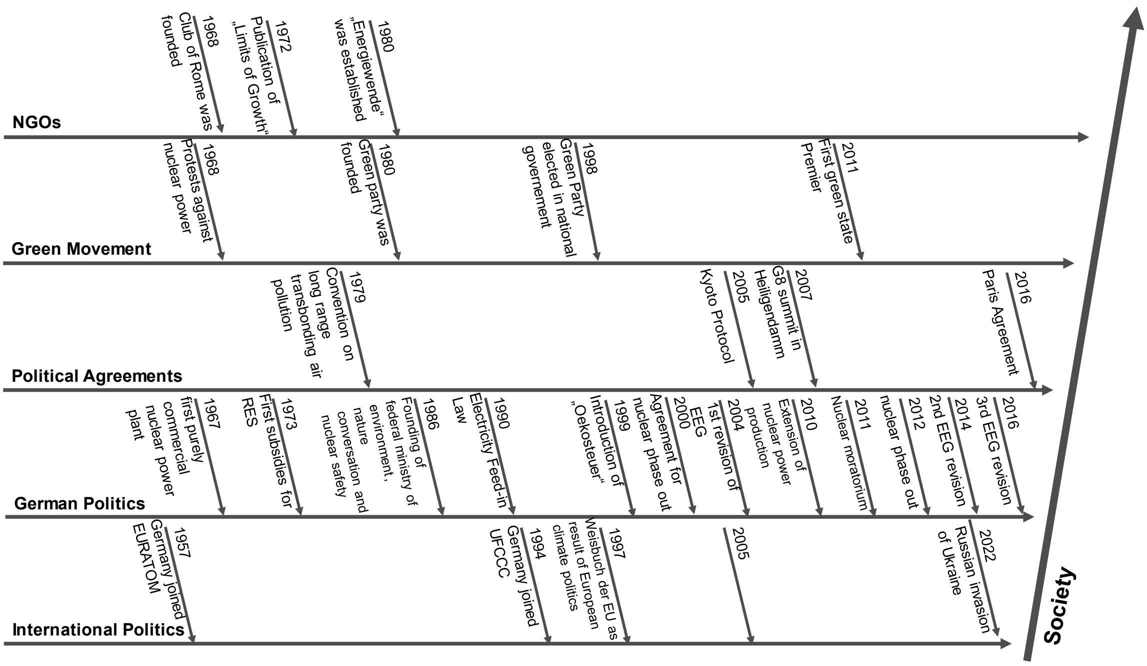

Figure 15: Societal and Political Factors

For the pillars of society and politics, we focus not only on policy measures of the German government but also on supra-national institutions and events resulting in far-reaching contracts and agreements. Since politics follow the consensus of society at least in part, it is important to consider the role of society as well. To do so, we decided to focus on NGOs as organized structures and the green or environmental movement in general – from now on "the environmental movement". Originally, the core agenda of this movement was, above all, the phase-out of nuclear power. In addition, it addressed the pollution in cities, and the movement advocated animal rights [90]. Over time, the environmental movement and its organizations emerged into a complex web of different influences, with many regional and thematic differences among its groups. In addition, a central line of conflict has not always been clear, which makes it even more difficult to define the environmental movement [91]

<u>(1) From WWII to 1968</u>: in West Germany, the Federal Republic was granted sovereignty as an independent state by the Paris Agreements of 1955 [92]. This event created the basis for establishing nuclear power as the second pillar of the German electricity supply alongside coal-based electricity generation. Immediately after the Paris Agreements took effect, the Ministry of Nuclear Affairs was created in 1955 [93], and in 1957 Germany joined the European Atomic Energy Community, EURATOM.

(2) From 1968 to the 1986 Chernobyl accident, the nuclear policy was supported by all the leading parties in Germany. Thus, even the change of government in 1969, with the first takeover of power by the Social Democrats (SPD), did not change the political position on power generation from nuclear energy [94]. At the same time, the Club of Rome was founded as a federation of scientists, who called attention to the limits of growth and natural resources as well as environmental risks. Backed by scientific concerns and other influences, anti-nuclear protests started in Germany and the 1968 student protest movement (68er-Bewegung) changed the country's society fundamentally [39]. The oil crisis in 1973 also contributed to a rethinking of the German energy policy for the first time. The aim was to increase independence from fossil fuels, especially those that had to be purchased from abroad. These developments triggered measures in two directions. On the one hand, the importance of nuclear power generation was emphasized once again, as this increased the country's independence from fossil resources. On the other hand, however, the first political effort was made to promote renewable energy sources. Around 10 million DM [5.1 million €] were made available to promote renewables in the 1970s, at this time almost exclusively photovoltaics. Even though this amount was fairly small, it was the first political subsidy for renewable energies in Germany [38]. This public funding was continued in the following years. In 1977, a twenty-five percent subsidy for investment in solar systems and heat pumps was introduced. However, as this subsidy was not sufficient to make such investments economically feasible, it was not broadly adopted, and remained almost without consequences [95].

In the years that followed, German society became increasingly critical of the increasing and high levels of emissions and water pollution. As a consequence of growing public pressure, environmental protection became an important topic on the political agenda. Thus, the "Convention on Long-Range Transboundary Air Pollution" was signed in 1979 to reduce air pollution as a reaction to the already mentioned Waldsterben of Germany's forests [96]. In 1980 the term "Energie-Wende" (nowadays: Energiewende, which means "transition of the energy system") was used for the first time in a publication by the Öko-Institut [97], which called for changes to energy politics in Germany as well as in all industrialized countries. It suggested a new way of supplying energy, which would be politically and socially advantageous, by decoupling economic growth and energy demand from primary energy sources. Energy efficiency played an essential role in the discussion to reduce energy demand in the long run. In the following years, the term "Energiewende" continued to be used and described the phase-out of fossil resources as the basis of the energy system. As mentioned, new scientific findings published by the Club of Rome and the Öko-Institut further raised public awareness for environmental topics and ultimately led to the founding and establishment of the Green party that emerged from the movement against nuclear power [98]. Even though the Green party did not enter the government until 1998, its influence was already obvious. In 1983, the “Greens” exceeded the five percent threshold and entered the Bundestag, the German parliament [99]. This was the first time that a party was represented in the German Bundestag which clearly opposed nuclear power and advocated the expansion of renewable energies [100]. The Chernobyl disaster in 1986 further accelerated the political change process and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz) was established in 1986 [101].

(3) From the Chernobyl accident to the Fukushima Accident the change in the mindset of German society and politics continued. In 1990, the law for the promotion of renewable energies (Stromeinspeisegesetz) was passed. For the first time, electrical system operators were obliged to feed-in the electricity generated from renewable sources into the grid. In addition, the companies were obliged to pay fixed rates for the “renewable” electricity fed into the grid [50]. For example, electricity from hydropower, landfill gas, and sewage gas as well as from biological residues and waste materials from agriculture and forestry was to be remunerated at a rate of at least 75% and electricity produced with PV systems or wind turbines at a rate of at least 90% of the average revenue per kilowatt hour.

In 1997, the “White Paper for a Community Strategy and Action Plan” of the EU was ratified. In order to mitigate climate change, the central point was to set the minimum share of renewable energy sources in gross domestic energy consumption at an average of 12% in 2010 for the entire EU. This document was the cornerstone of the pan-European climate policy, as it established the idea of burden-sharing within the EU and also referred to the outstanding results of the climate conference in Kyoto at that time, on the basis of which more precise targets were agreed [102]. The Kyoto conference in the same year is still seen as the most groundbreaking world climate conference to date. After long negotiations, various targets for the reduction of CO_2 emissions were adopted there. For the 15 member states of the EU at that time, a total reduction in emissions of 8% was set for the period 2008-2012 compared to the base year 1990 [103]. The idea of burden-sharing was implemented in the Kyoto Protocol as well and formed the basis of the EU Emissions trading scheme (EU ETS), first introduced in 2005 [104].

In the coming years, several additional measures to transform the energy system were implemented. With the entry of the Green party into the government in 1998, the phase-out of nuclear energy was brought forward [105]. In agreement with the operators, a decision was made to phase out nuclear power plants (NPPs) without compensation payments and the remaining time of already operating NPPs was limited to 32 years. In the year 2000, the Renewable Energy Sources Act (Erneuerbare Energien Gesetz; EEG) was passed with the votes of the Social Democratic party (SPD) and the Green party. The aim of this law was to initiate a sustainable energy supply. The share of renewable energies in electricity generation should be at least doubled by 2010 in accordance with the above-mentioned targets of the European Union and the Federal Republic of Germany itself. The core of the law comprised fixed feed-in tariffs for electricity from renewable sources [51]. Grid operators had to feed-in electricity from renewable resource and to pay fixed prices per kWh independently of when and how much energy was generated. Wind was initially enumerated with 9.10 ct/kWh in the first five years and then decreased step by step to 6.19 ct/kWh. PV was initially enumerated with 50.60 ct/kWh [51]. The additional costs from the EEG were paid by all consumers. The corresponding EEG levy was introduced for this purpose, which must be paid by all consumers in proportion to their electricity consumption. Specific industries could be exempted depending on their dependence on electricity. In addition to that, the government introduced the so called eco-tax (Ökosteuer), which again increased the prices for the customers by another 2.05 ct/kWh [55]. However, the EEG has not only led to rising electricity prices, but has also ultimately laid the foundations for the economic viability of electricity from renewable energies. With the feed-in tariffs being in general much higher than the cost per KWh generated with fossil fuels or nuclear power, the EEG has therefore contributed significantly to the economic changes in the energy market discussed above. The EEG thus formed and continues to form a milestone for the transition of the German energy system.

In 2002, the coalition government pushed ahead with the phase-out of nuclear power generation. Shortly before the end of its first legislative period, the coalition of the Social Democrats (SPD) and the Green party passed the Act for the Orderly Termination of the Use of Nuclear Energy for the Commercial Generation of Electricity (Gesetz zur geordneteten Beendigung der Kernenergienutzung zur gewerblichen Erzeugung von Elektrizität) [106]. As a result, two key decisions were taken: there was a ban on the construction of new nuclear power plants, and it was decided the regulations would lead to the last nuclear power plant going off the grid in 2021 [106]. Development in the area of renewable energy sources was to be continued as well. The first amendment to the EEG was adopted in 2004. This affected the feed-in tariffs for wind turbines. The period for the initial remunerations of onshore wind turbines was increased to five years before a basic remuneration was guaranteed. For offshore wind turbines, the period for the initial remuneration was at least twelve years. In addition, the law was adapted to European framework conditions [107].

The federal elections in 2005 resulted in a coalition of the three major parties CDU/CSU and SPD but did not put a hold on the transition of the energy system. The new coalition agreed on further promotions of renewable energies. Contrary to previous statements, the CDU/CSU no longer opposed the EEG. The government agreed on clear targets for the development of renewable energies [108]. However, the disagreement about the future development of nuclear energy remained unchanged. While the Social Democrats (SPD) sought to further accelerate the nuclear phase-out, the Conservative CDU/CSU argued in favor of maintaining the existing plans.

On the international level, the G8 forum decided to reduce carbon emissions by 50% by 2050 [109]. In addition to these fundamental changes, international politics focused on further factors with considerable impact. In 2005, the EU Emissions Trading System, EU ETS, was introduced, allowing burden-sharing between member states according to the Kyoto Protocol. The EU ETS also put a cap on industry-based carbon emissions. Within the cap, companies receive or buy emission allowances for greenhouse gas emissions. Several platforms, such as the EEX Leipzig, permitted direct trading of these allowances. As the energy sector emits most of the CO_2 emissions in Germany and in the EU [110], companies belonging to the energy sector were most concerned by the EU ETS [55]. In 2007, the G8 summit in Heiligendamm (Germany) was held and was accompanied by strong protests from environmental activists. After widespread debates, the summit ended with a common declaration for international climate protection [39].

In 2005, when the EU ETS was introduced, Germany created the Federal Network Agency (FNA; Bundesnetzagentur) in the same year. The aim of the FNA, a regulatory office for electricity, gas, and communication markets, is to foster the competition in the energy market by guaranteeing non-discriminatory grid access [111]. Respective measures have been accompanied by grid access for the many decentralized electricity suppliers, e.g. operators of PV panels, which are thus treated equally as large power plant operators in terms of grid access [112].

Meanwhile, the political decisions became more critical towards a faster transition of the energy system in Germany. In this vein, the federal government extended the lifetime of existing NPPs by an average of 12 years to use nuclear power as a bridge technology for the energy transition [113]. Moreover, 90% of the income of 17.5 billion € of the Ökosteuer (eco-tax) was used to finance the pension insurance budget and only a small amount of the tax was used to support renewable energy [55]. Besides that, some argued that the mechanisms of supporting renewables and the subsidies for renewable energy generation imposed “high costs without any positive impacts on emission reductions, employment, energy security, or technological innovation” [112]. While Germany was already well known for its leading role in the transition of its energy system, (see [114]), some of the regulations implanted during this period did not further promote the underlying processes [112]. However, the political and societal mindsets changed dramatically with the 2011 accident in Fukushima.

(4) From the Fukushima accident to today, society and politics have focused on the phase-out of NPPs and of fossil power plants. Following the accident on March 11, chancellor Merkel announced a nuclear moratorium only four days later on March 15. This moratorium obliged NPP operators to shut down the seven oldest reactors immediately with the reference to a security paragraph of the Atomic Energy Act (Atomgesetz) [39, 115]. A remarkable outcome for German society was the election result for the state government of Baden-Württemberg on March 27, 2011. For the first time in Germany’s history, one of its federal states elected a minister president from the Green party, even though Baden-Württemberg had been known as a conservative state dominated by the Christian Democrats (CDU) for more than five decades [116].

While energy prices increased substantially over time due to the higher share of electricity from renewable energy sources, society has held on to this development [117]. During the period from 2002 to 2020, the share of electricity from renewable energies (water, bio mass, wind, and solar) in Germany rose from 8.65% to 53.14% [118]. This sharp increase was a result of an agreement between the federal government and major power utilities for the nuclear phase-out without compensation payments [39], and the subsequent law for phasing out all NPPs by the year 2021 [119]. After the Fukushima accident, the EEG was repeatedly revised (2012, 2014, and 2016). The central challenge of the adjustments made was the sharp rise in prices for end-consumers as a result of the EEG levy and the simultaneous insufficient increase in the number of production facilities. Especially the share of PV increased since 2010, as can be seen in Figure 16 [118]. However, as PV plants can be seen as private investments with fixed and subsidized revenue, the EEG has had a crucial role in the German energy transition. Despite all criticism, German society still supports this policy. In a survey, 88% of the respondents expressed their support for the transition process [117]. Many promotors even endorse a faster transition to mitigate climate change. For instance, in 2018 protests against lignite power plants mobilized more than 36,000 people in Germany [120]. These protests led to the creation of the so-called "Coal Commission" (Commission on Growth, Structural Change and Employment), which developed a recommendation for political decision makers on how to phase-out coal- and lignite-driven power plants in Germany by 2038 [121]. This recommendation was agreed on by the German Bundestag in 2019 and resulted in the Coal Phase-out Act (Kohleausstiegsgesetz).

In the 2021 federal election, the Green party was able to improve its total vote by more than 50% and to achieve renewed government participation [122]. As a result, responsibility for climate protection, among other things, was transferred to the Green-led Ministry of Economics [123].

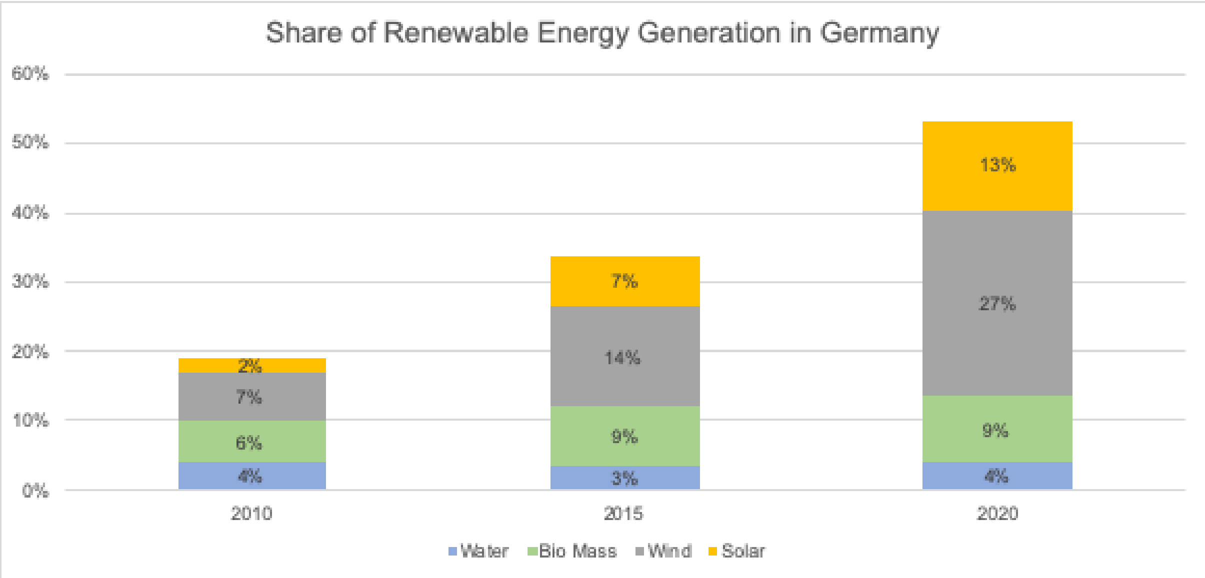

Figure 16: Share of Renewable Energy Generation in Germany

<u>(5) Russian invasion of Ukraine</u>

The Russian war against Ukraine is an example of an event that accelerates ongoing changes in the energy system, but it also shows the complexity of decision-making due to different interests and necessities in energy policy. As already described in the sections Environment and Economy, Germany made itself dependent on Russian oil, especially gas supplies. Even though there was a political will to economically isolate Russia at the beginning of the war, which was implemented in many sectors, trade in fossil fuels was not immediately suspended out of concern for economic damage to Germany. The fact that the Minister for Economy and Climate Change Mitigation from the Green party went to Qatar – a country criticized for human rights violations – in order to negotiate supplies of LNG, shows the tension in which energy policy decisions sometimes have to be made [124]. The picture is complemented by the Liberal

Finance Minister, Christian Lindner, who introduced state subsidies in order to reduce petrol prices, which had risen after the start of the war [125].

Overall, the political decisions which led to the ongoing transition of the German energy system were influenced both by complex interactions of various stakeholder groups and by singular events. In addition, the environmental movement established a strong political force in the Green party, which has linked scientific findings on climate change and other environmental impacts with its political positions.

Technological Improvements

The perspective of technological improvements describes developments in the fields of wind and PV technologies, and a general category, which reflects the progress in other areas, such as electrical grids, hydrogen production, nuclear power or emerging smart technologies. Along with the policy measures discussed above, these technological improvements led to substantial efficiency gains in favor of an increasing share of electricity from renewable energy sources, and resulting in a shift of the underlying costs discussed when focussing on the economic pillar.

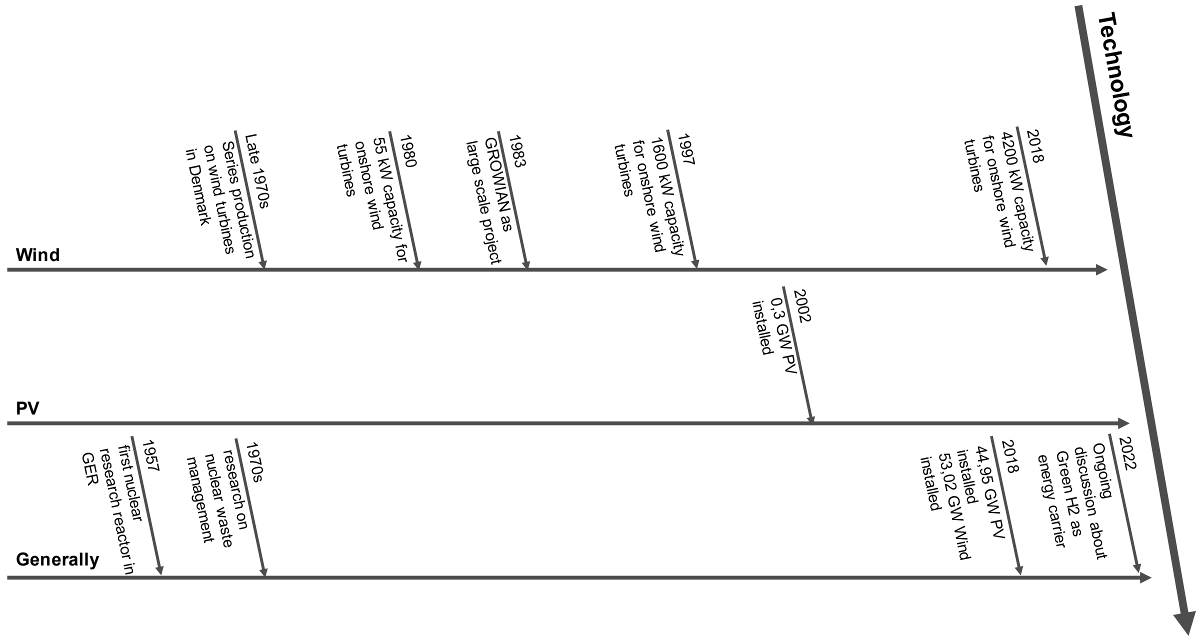

Figure 17: Technological Improvements

<u>(1) From WWII to 1968</u>, the economy was growing fast in West Germany and more energy was needed, which required new power plants as well as new power lines. After the world's first nuclear power plant (NPP) to supply an electricity grid was commissioned in the Soviet city of Obninsk in 1954 [126], and the world's first full-scale power plant with nuclear power opened in Calder Hall in England in 1956 [127], Germany also focused on building its first

NPP. In addition to existing power generation methods, Germany started to use nuclear power in the 1950s and built the country's first nuclear research reactor in 1957 [39, 128]. In order to successfully advance nuclear energy and to become less dependent on the economically weakening domestic coal industry, several nuclear programs were set up in the years 1955, 1963, 1967, and – as a consequence of the oil crisis – in 1973 [129]. These programs financed research and development activities as well as extensive training courses for nuclear physicists, radiation experts and engineers for the operation of nuclear power plants. Due to a lack of experience and to the tremendous brain drain prior and during World War II, a completely new workforce of engineers and technicians with professional knowledge in this area had to be built up. All these efforts were successfully pursued, and in 1967 the first purely commercial NPPs in Germany began their operations in Würgassen and Stade. In the same year, the first German nuclear waste storage facility was opened at the Asse mine in the federal state of Lower Saxony.

<u>(2) From 1968 to the 1986 Chernobyl accident</u>: After the opening of the first NPPs, the activities of German nuclear research shifted towards waste management and unrelated new technologies like microelectronics, computer technologies, and environmental science [128]. In parallel, the first oil crisis along with increasing fuel prices and mounting supply risks improved the economic advantages of nuclear power and made Germany more independent from the importing of fossil resources [130].

At the same time, other countries started to increasingly focus on energy from renewable sources. In Denmark, for instance, the use of renewable energy was already supported at this time. Danish companies started to produce wind turbines in series in the late 1970 [39], leading to technological improvements in on- and off-shore wind turbines. German energy companies tried to profit from these improvements and invested in first pilot projects [39]. For example, the Growian project was launched in 1983. A wind turbine with a rotor diameter of 100 m and 3 MW power was planned as a demonstration project for large-scale wind energy transition. However, due to technical problems, the project was closed only two years later in 1985 [131].

<u>(3) From the Chernobyl accident to the Fukushima accident</u>, the capacity of a single wind turbine increased from 150 kW in 1986 to 6,000 kW in 2007 and the rotor diameter rose from 25 m in 1986 to 127 m in 2007 [132]. Furthermore, the costs for rooftop PV systems of up to 10 kW_p halved in the years from 2007 to 2011 [133].

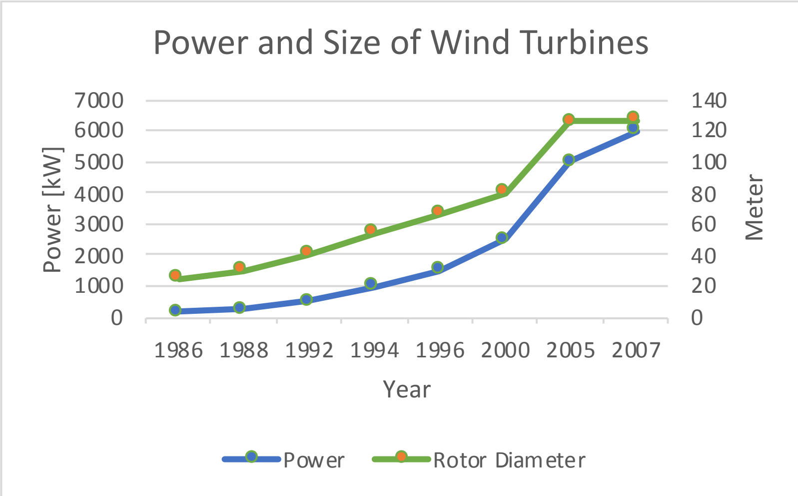

Figure 18: Power and Size of Wind Turbines

(4) From the Fukushima accident to today, and already some years prior to Fukushima, research in alternative energy production has intensified. In 2009, the German government agreed on subsidies to compensate for the lack of competitiveness of new technologies. The EEG regulated the remuneration of electrical energy produced by renewable sources, including biogas, wind, and PV. Even though PV was the most expensive technology to generate electricity from renewable sources, it was the financially most supported one [112]. Hence, the installed PV capacity rose from 0.3 GW in 2002 to 51.99 GW in 2020. But onshore wind energy generation also increased from 11.98 GW in 2002 to 54.14 GW in 2020 [134]. Technological progress has contributed, among other things, to the fact that the gross generation of electrical energy in on- and off-shore wind turbines increased to more than 100 TWh per year in 2017 [135]. The current maximum capacity of a single on-shore wind turbine is up to 4,200 kW with a rotor diameter of 127 m [136].

Furthermore, there are ongoing discussions about green hydrogen as an energy carrier, since there is already an established infrastructure, and hydrogen could be used as storage for electricity in peak times. With increasing costs for fossil fuels, the production of green hydrogen is becoming even financially an alternative. [137].

(5) The Russian invasion of Ukraine

The war in Ukraine has not led to any concrete technological improvements so far. Thus, the integration of the electricity grid into the ENTSO-E has already taken place and has been brought forward by one year [138]. However, the abandonment of the Nord Stream 2 project demonstrates the political willingness to change the financing and funding of individual technologies, too. If the German operating company is banned from commissioning or denied certification, it could face claims for damages amounting to €10 billion [139]. Hence, the political and economic necessity of an increased energy autarchy will certainly increase the promotion of technologies related to renewable energy production.

In summary, technological improvements on the one hand have enabled the energy transition; on the other hand technological progress also poses a limitation to even faster and more comprehensive changes. The development of renewable technologies that can quantitatively and qualitatively cover the needs of both society and the economy has been a lengthy process, as the infrastructure, such as electricity grids, has had to be adjusted as well. Nevertheless, huge improvements of several technologies that rely on renewable energies have substantially contributed to the ongoing transition of the German energy system. It can be expected that the Russian invasion of Ukraine will further accelerate this process.

1.3.2 Causes and Effects

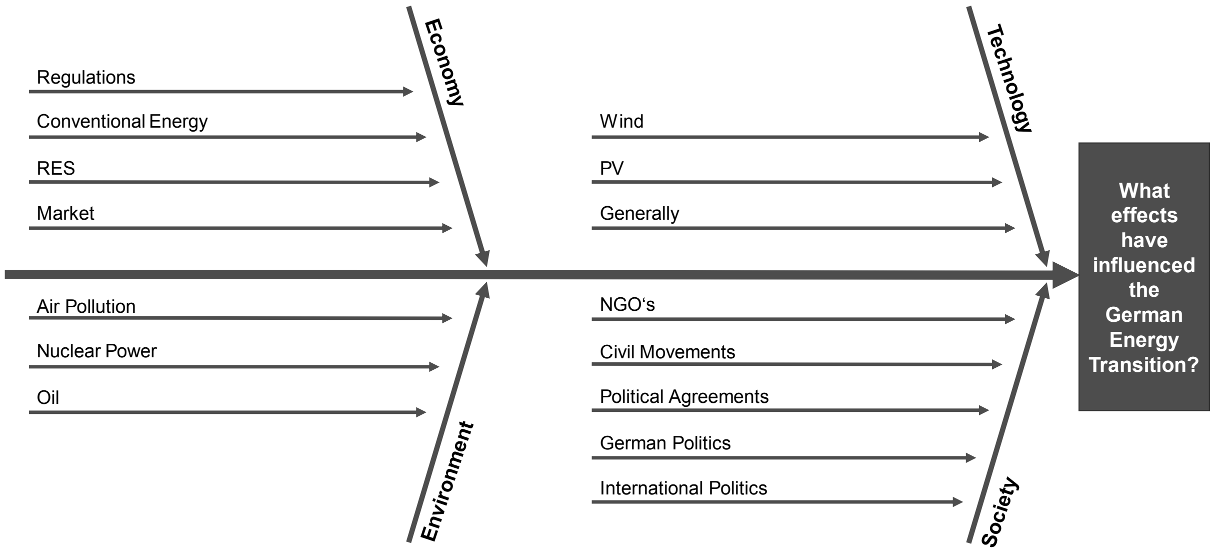

Figure 19: Ishikawa Diagram, Causes and Effects of the German Energy Transition

Having documenting the relevant influencing factors for the German Energy Transition, the following section will show the interactions between the individual factors. Not all cause-effect relationships can be objectively demonstrated, but it is essential to understand the Energy Transition in its entire complexity in order to visualize the most important interactions. We will now examine the four perspectives together, while retaining the temporal structure of the previous chapters.

<u>(1) From WWII to 1968</u>: At the time of Germany's economic development, there was one maxim for the provision of electrical energy: As the backbone for the development of Germany's economy, the energy supply needed to be inexpensive and efficient. Accordingly, government and political parties backed and supported this focus towards economic growth:

early on, active nuclear policy was pursued by establishing the Atomministerium (Ministry of Atomic Energy), which promoted and enabled the development of commercial nuclear power generation.

(2) From 1968 to the 1986 Chernobyl accident: Initially, the electricity supply in Germany was based mainly on fossil fuels. At the same time, the first negative effects of this policy became visible: the population in some regions, especially in the heavily polluted Ruhr area, was suffering from various medical problems. This also had an impact on politics: air pollution was an issue in the 1974 election campaign but did not lead to a general negative attitude towards the status quo of existing and installed energy technologies.

The oil crisis can be seen as the first external trigger. The German public became aware of the great dependence on fossil (and imported) energy sources, and this strengthened the will of all parties to promote nuclear power generation. This enabled the electricity producers to develop a second mainstay while securing great potential for significant earnings. The outcome was a system of fossil and nuclear energy sources with low electricity prices and good earning opportunities for the energy utility companies, supported by politics.

This system raised awareness of mounting environmental problems: the first nuclear accident occurred in Harrisburg, USA, in 1979 and – concerning Germany – noticeable environmental damage, such as acid rain and forest dieback. This resulted in growing environmental concerns among parts of the population. The so-called "Green Movement" was formed, culminating in the foundation and later entry into the German parliament of the Green party. First steps in renewable energy production were made. For example, the development of new wind turbines made great technological progress in the 1980s but – without any political support at that time – no success could be achieved.

(3) From the Chernobyl accident to the Fukushima accident: Another external trigger was the Chernobyl disaster. The radioactive accident dramatically highlighted the dangers of nuclear power generation and created a general political awareness of the need for environmental protection measures. The Green Party in Germany was no longer isolated with their positions in parliament. As a consequence, the Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety) was established. In this case, it was an external event which triggered changes in political objectives that had already taken place among parts of the population at an earlier stage.

In 1990, the first step towards the active political promotion of renewable energies beyond the funding of research and pilot projects was the Electricity Feed Act (Stromeinspeisegesetz), although this law had few consequences at the onset. However, awareness of the need to reduce the emission of greenhouse gases was growing internationally, too. With the Kyoto Protocol and the first EU-wide regulations for emission reduction, Germany agreed to intensify its efforts to reduce greenhouse gas emissions.

With the entry of the Green party into the German Federal Government in 1998, nuclear skeptics and representatives of the environmental movement, which had been running for almost 20 years, came to power for the first time. This also had immediate consequences. In 2002, the Atomgesetz (Atomic Energy Act) was passed, which stipulated that all nuclear power plants should be shut down by 2021. This act provided planning security for the energy companies as to when their profitable "cash cows" would be shut down.

At the same time, the first version of the EEG (Renewable Energy Sources Act) was introduced. With the feed-in tariff and the exception of the Merit Order, the share of renewable energies rose rapidly. Now, the market liberalization that had been implemented years earlier was having consequences. The profitability of the energy companies' base-load and peak-load power plants declined. The will of broader parts of German society was translated into political measures with immediate economic impact as soon as the promoters of renewable energy generation gained a political majority. New subsidies (1st amendment to the EEG in 2004) also led to rapid increases in the output of wind and solar power. It became clear that – with the appropriate political measures – the success of green technologies could be secured, including their further technological development.

In 2005, the Green party had to leave the government and there was disagreement between the conservative Christian Democrats (CDU) within the coalition and the Social Democrats (SPD) regarding the nuclear phase-out. After the following elections, the Christian Democrats and the Liberals (FDP) formed a government. In 2010, using their majority in the Bundestag they extended the remaining operating life of German nuclear power plants again [140]. This change in the political course created a certain amount of economic uncertainty for energy providers and technology companies.

<u>(4) From the Fukushima accident to today</u>: The extension of the lifetime of nuclear power plants deviated from the long-term political line and somewhat contradicted the social opinion, which became apparent in the wake of the Fukushima disaster in 2011. Within a few days, the German government agreed on a shutdown of the oldest nuclear power plants as an immediate

consequence. The population also reacted strongly to this event: surprisingly, the first Green minister-president of a German federal state was elected shortly afterwards. The remaining lifespan of nuclear power plants was shortened again. Once more, an external trigger had intervened and changed the political course with direct economic consequences.

In the further course of events, the volume of renewable energy production increased in line with the political will of major parts of the German population, supported by further amendments to the EEG. This led to a further decline in market prices for electricity, and periods with negative market prices for electricity were rising significantly in duration and frequency. This also weakened the economic role of the fossil fuel-based power plants that still played an important role for the established large energy companies.

The reaction to this development from the energy companies came late: in 2018, a necessary restructuring of the major energy companies, such as E.ON and RWE, took place, separating the new business areas from the expiring fossil-based business models. In the end, political conditions had initiated a change within the largely regulated energy market, which created new players and shifted circumstances, to which the established players had to react after a prolonged hesitation. This development culminated in the decision to phase out coal power plants by 2018, a decision which was politically settled – partly due to growing social pressure – after long disagreement.

<u>(5) Russian invasion of Ukraine</u>

At the beginning of the war in Ukraine, Germany was highly dependent on oil and especially gas supplies from Russia. Due to this great dependency, the economic sanctioning of Russia could not immediately be implemented in the energy sector, unlike in other sectors, despite the basic political and societal will in Germany. Nevertheless, the event made the public aware of this dependency and all its disadvantages. The necessity of an energy transition towards renewable energy sources was thus given further political and economic emphasis in addition to the environmental justification. Once again, a single event was the trigger for assessing a situation that had already existed for a long time differently than before and triggering actions that had been postponed until then.

1.4 Categorization of the Interactions and Interdependences of the Different Perspectives

1.4.1 Results

In the context of the German energy transition, the distinction between cause and effect is not always unambiguous. The diagram shows the different paths which have had an impact on the transition of Germany's energy system. Interdependencies between the different factors affect actions and reactions and foster developments in other categories or regarding other pillars of the sustainability concept. In the process of understanding and analyzing the German energy transition, we have derived four conclusions from the causes and effects discussed in the previous chapter which abstract general explanations for the sequence of events.

Finding 1:

Environmental disasters and other environmental incidents have been triggers in Germany's energy transition process.

As shown in section 1.3.1, with regard to the environmental pillar, we have discussed incidents with high environmental impact as well as long-term effects, such as the impact of air pollution on the use of fossil resources. These incidents and their interactions with the other pillars investigated and discussed in section 1.3.2 show that there is no sole or direct impact on political or economic decisions. Nevertheless, it can be seen that every environmental incident has pushed the interaction of politics and society. For instance, the smog in the German Ruhr area caused politics to focus on emission targets. The Chernobyl accident strengthened the anti-nuclear movement in Europe. In the same vein, the Fukushima accident was the reason for Germany's nuclear moratorium. These examples illustrate that events with high impact on the environment have not defined the fundamental path of politics or society but have provided decisive impulses. The Fukushima accident and the ensuing moratorium provide a good example of "the straw that broke the camel's back". The Fukushima disaster alone would not have had any consequences if there had not been an ongoing discussion about nuclear energy in Germany. In conclusion, environmental disasters have been triggers, but no (sole) drivers of the process of energy system transition. This conclusion can also be derived from the fact that the accident provoked different reactions from Germany's neighbouring countries.

Finding 2:

The sector of energy generation is heavily driven by political regimentation. The developments are mainly influenced by political requirements.

Energy generation and distribution used to be a natural monopoly or oligopoly, due to technical restrictions. Supplying energy at low cost and with high reliability is a crucial economic and societal factor for any country, thus making the government an important stakeholder. In consequence, the political objectives for energy generators and suppliers are not only determined by technical requirements but can be politically and economically motivated. As section 1.3.1 shows, after World War II the political will in Germany was to support inexpensive and reliable large-scale power plants, with a centralized structure for supply. Once a running system had been installed, large investments into power plants and infrastructures defined the roadmap of energy companies for decades. Similarly, political forces drove the introduction of nuclear power generation. Later, when the transition of the energy system towards sustainability had been established as a political goal, the requirements for generating and supplying energy changed. Politics changed the focus from an inexpensive and reliable energy supply towards a renewable and reliable energy supply, which not only led to some drastic changes from a technological perspective but which also required substantial changes in government subsidies. In parallel, the liberalization of the energy market scheme was established where more and more rules have been adopted to open up electricity generation to large sectors of the population and to smaller companies. The introduced market rules were enforced by regulations and subsidy schemes introduced by government to support renewable energy generation.

Finding 3:

Political requirements and legal regulations have been determined by macroeconomic and societal demands. Following these factors, the political objectives have undergone a consistent conversion over time.

The aim of politics is to act for a society rather than promoting established structures and companies. Although the political framework supported large-scale energy generation in the first decades after World War II, the tendency towards less harmful emissions and reduced air pollution became apparent in political actions. Already in 1974, air pollution was a topic in Germany's election campaign. At the end of the 20th century, clear signs of a fundamental change in the energy sector towards more sustainability were recognizable. This change took place despite the fact that Germany is a country with a high demand for electricity, and at the same time with geographically few possibilities for generating renewable electricity from hydropower. From a macroeconomic perspective, the implementation of a market scheme was introduced in 1990 and expanded step by step. This introduction was also an expression of societal demands. The strategy towards the energy transition became more apparent over time. The most important cornerstones were the introduction of a market scheme, subsidies for the generation of electricity from renewable sources, separating energy companies into generators and system operators, and discrimination-free grid access. Furthermore, the Federal Network Agency (Bundesnetzagentur) was established to monitor these targets. Moreover, politics sent another signal towards energy companies with the election of the Green party into the government in 1998. Seven years later, with the re-election of the conservative Christian Democrat government, the political strategy was interrupted by the prolongation of the nuclear phase-out, which was cancelled again after the Fukushima accident and changed towards a shorter phase-out. Leaving out the latter, the political roadmap went steadily in one direction towards the energy transition, in line with societal concerns and demands.

Finding 4:

Energy companies had followed the tendencies determined by political decisions and regulations, as well as subsidies for a long time, but then missed the chance to properly and timely adapt their business models.

As discussed, the political framework supported large-scale and inexpensive energy generation in the first post-WWII decades. Also, nuclear power plants were supported politically for a long time. Substantial investments and the oligopoly market structure made energy companies large and inflexible, but this situation was also politically desired. After the first signs of market liberalization, energy companies reacted only slowly to the changing market conditions. This became apparent not only in their focus on large fossil power plants, but also in a hesitant investment strategy towards renewable generation technology. Instead, the large energy companies set about lobbying the government in order to reap profits from their traditional fossil-based business models, which led to the postponement of the nuclear phase-out and established the political term of “Bridging Technology” for nuclear power plants. Since the nuclear moratorium of 2011, the companies took legal action to obtain compensation for shutting down nuclear power plants. A similar procedure can be seen with the operation of lignite-driven power plants. Substantial organizational changes were implemented when the corporations’ business models eroded and profit numbers fell substantially. In summary, we conclude that the political path towards Germany’s energy transition was largely predictable already by the end of the 20th century, but large energy companies in Germany missed the chance to adapt their business models properly by ignoring long-term changes in societal perceptions and political regulations.

1.4.2 Discussion of the Outcomes and Answering the Research Questions

This paper addresses the following two research questions: (1) *What effects have played a substantial role in the German energy transition and how have they interacted?* and (2) *What regulations have influenced companies in the energy sector during the German energy transition?*

Based on our work described above, we can state the following regarding the first question: All four factors described – economic, ecological, societal/political, and technological – have impacted the German energy system transition. The interactions between the influencing factors have shaped the path towards more sustainability of the country's energy system.

We were able to show that political measures and regulations were the decisive drivers of changing the energy market. In turn, political action in this area was influenced by two factors: economic demands on the central element of energy supply and societal demands that had a long-term impact via processes that form opinions in political parties and via election results. Environmental influences alone did not drive the process forward. However, individual environmental accidents along with predictions from science, e.g., the reports compiled for the Club of Rome or climate change reports by the IPCC [141] were either the impulse or the final trigger for social and political processes. It is remarkable that technological developments only had a minor influence as an initiating element in the process of transforming the national energy system. New technologies and business models could only be established with proper political support.

Regarding the second question, our investigations revealed the following. For several decades, the energy companies had relied on operating large centralized power plants. This approach was supported politically and was intensively promoted, especially in the case of nuclear power generation. As the political will shifted towards renewable energy, the framework for generators was gradually transformed. The Electricity Feed Act (Stromeinspeisungsgesetz) of 1990 and the market liberalization of 1998 left the producers mainly untouched, so they stuck to their established strategies. It was not until the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz (EEG)) in 2000 and the exemption of renewable energies from the Merit Order that the energy companies were affected. At the same time, the nuclear phase-out had been prepared. Despite both developments, the energy companies held on to their sources of revenue and only started to convert to renewable energies after a long delay. Several rounds of amendments to the EEG strengthened the transition of the German energy system towards more sustainability. However, it is also clear that further action is necessary with regard to both achieving the climate change goals and becoming more independent from external sources, as the consequences of the Russian invasion of Ukraine have impressively shown.

1.5 Conclusion

The present paper shows influence factors which have been related to the process of energy transition in Germany since World War II. These factors are divided into four categories: The three pillars of sustainability (environment, economy, society) are considered, as well as a fourth pillar of technology. First, the different factors for each category were described in chronological order. In a second step, the four perspectives were integrated in a chronological cause-and-effect analysis for each of the categories. These cause-and-effect analyses, allowed us to investigate the complex interdependencies between the different factors, but also to determine that some factors are individually important, while others are contradictory or supportive of each other. Analyzing the overall picture, this paper shows that each pillar takes on a certain role. The pillar of the economy sets the starting position, which is relevant and valid over a long period. The pillar of society and politics sets the regulative framework for the different actors, based on the perceptions and demand among large parts of society. Hence, this happens by taking singular events into account and via ongoing discourses and interactions between society and politics. Environmental factors trigger the development in politics and society, which leads to changes in the economy. Finally, the pillar of technology is more marginalized in terms of causes and effects on the other pillars than one might expect. The investigations show that technologies provide the opportunities for major changes and improvements, but do not initiate them in the first place. Instead, technologies and their further development fulfill the needs set by new regulations and the economy.

In conclusion, waiting for technological leaps before implementing a fully renewable energy system is not a promising strategy. This study has identified social movements that have translated into political actions and regulations as the main drivers for the energy transition. These movements set an economic environment and defined requirements as well as demands towards the development of technologies. In this vein, energy companies must observe their regulatory and social environment and their stakeholders' will in order to avoid missing substantial transformations. An enhanced agility of the major utilities is necessary for this to happen. Overall, our cause-and-effect analysis has shown that the entire energy system transition is a complex and path-dependent process, which is driven by multiple factors, and many different stakeholders have significant stakes in the related developments.

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2 Research Paper 2 – Optimisation of Photovoltaic and Battery Systems from the Prosumer-oriented Total Cost of Ownership Perspective

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Abstract

Background

In the context of the German energy transition, the number of domestic households covering part of their electricity consumption from their own photovoltaic system is constantly increasing. Some even use battery storage systems to store excess power for later use, which increases the degree of self-sufficiency and, according to the providers of such systems, should yield financial advantages for the so-called prosumer.

Methods

We used the Prosumer-oriented Total Cost of Ownership method to analyse the financial possibilities for prosumers under German market conditions, and thus determined the economically optimal solution for different domestic household sizes. In order to obtain realistic results, we applied real data covering the weather (relevant for the generation of electricity), consumption patterns, investment and operating costs, prices and revenues. If behavioural aspects are set aside and pre-requirements (e.g. sufficient roof space) are met, our model provides guidance for investors and policy makers alike.

Conclusion

Our research shows that it is financially advantageous for all household sizes to operate the largest photovoltaic system possible for them (up to 10 kW_p). By contrast, our results show that the investment in a battery storage system does not pay off even when government subsidies are taken into account. Regardless of the size of the selected battery storage system and all other influencing variables, the financial advantages of such a system do not materialise, although a battery storage system does substantially increase the self-sufficiency rate.

Keywords

Total Cost of Ownership; PV System; Battery Energy Storage System; Prosumer; Discrete Optimisation; Energy Transition

2.1 Background

2.1.1 Introduction

The transition of the German energy system is a huge challenge for policy makers and is absolutely necessary if emissions are to be reduced. However, this transition cannot be successful unless a broad participation of energy producers and energy consumers is achieved and their efforts are well coordinated and aligned with each other [1–3].

In 2009, the European Parliament already enacted the goal of a 20% improvement in energy efficiency by 2020 compared to 1990 [4]. It also "endorsed a mandatory target of a 20% share of energy from renewable sources in overall community energy consumption by 2020 and a mandatory 10% minimum target to be achieved by all Member States for the share of biofuels in transport petrol and diesel consumption by 2020, to be introduced in a cost-effective way" [4]. For a long time now, Germany has been regarded as the leader of the energy transition. Even the German expression "Energiewende" has been adopted worldwide. In 2010, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety focused on a more decentralised renewable energy generation and consumption with a better integration of renewable energy systems (RES) in the energy mix.

To facilitate this, the development of the electricity grid was identified as a mandatory factor − both in terms of capacity (installing the new lines needed as well as adapting already installed ones to changed needs) and quality (such as making the grid more efficient by avoiding losses). These efforts should be accompanied by an expansion of energy storage systems [5]. Hence, the German government has involved citizens of Germany in large incentive programs. In 2010, photovoltaics (PV) only generated 9% of the electrical energy but incurred 40% of the incentive costs [5]. Although the European Commission had determined PV as a leading-edge technology with high potential for exports in a very competitive global market [6], electricity generation with PV had only reached 6.1% in Germany by 2017 [7]. Following the IPCC Special Report Global Warming on 1.5C, PV solutions for prosumers with increasing self-sufficiency will become more important [8]. Despite these high ambitions and even though some authors attest the German energy transition as "the core of a comprehensive strategy to redirect Germany onto a future-oriented and sustainable path" [9], Germany will not only fail its own climate goals but also its European obligations [10]. In fact, it is very likely that Germany will also fail to meet the target set in the coalition agreement of generating 65% of its energy from RES by 2030 [11]. Even though the transition of the German energy system in general is not the focus of this study, the change towards a bottom-up market structure involving prosumers will accelerate the energy transition on the whole [1].

The share of decentralised generated electricity, often at the locations where it is consumed, will increase. These decentralised generation entities, in particular prosumers, will have to be integrated into the future grid in order to support the system's stability and efficiency [13]. Figure 20 illustrates the current top-down model of the electricity supply on the left side, while new participants and multi-level exchange structures will arise in the future (right side). The European Parliament supports the goals of lowering the connection costs and ensuring an equal treatment of consumers in rural and city areas [4]. Since energy generation in a bottom-up market model is a ground-breaking change, the new situation for consumers and prosumers needs to be evaluated financially [14]. However, not only will the electricity market change because of this new model; direct current (DC) generation (PV), the need for energy storage, and new connection technologies will also fundamentally affect the electricity market.

In this paper we examine the disruptive and new market player — "the prosumer" [15] — and evaluate the different scenarios of production, storage and self-consumption with a focus on the financial consequences and based on real data.

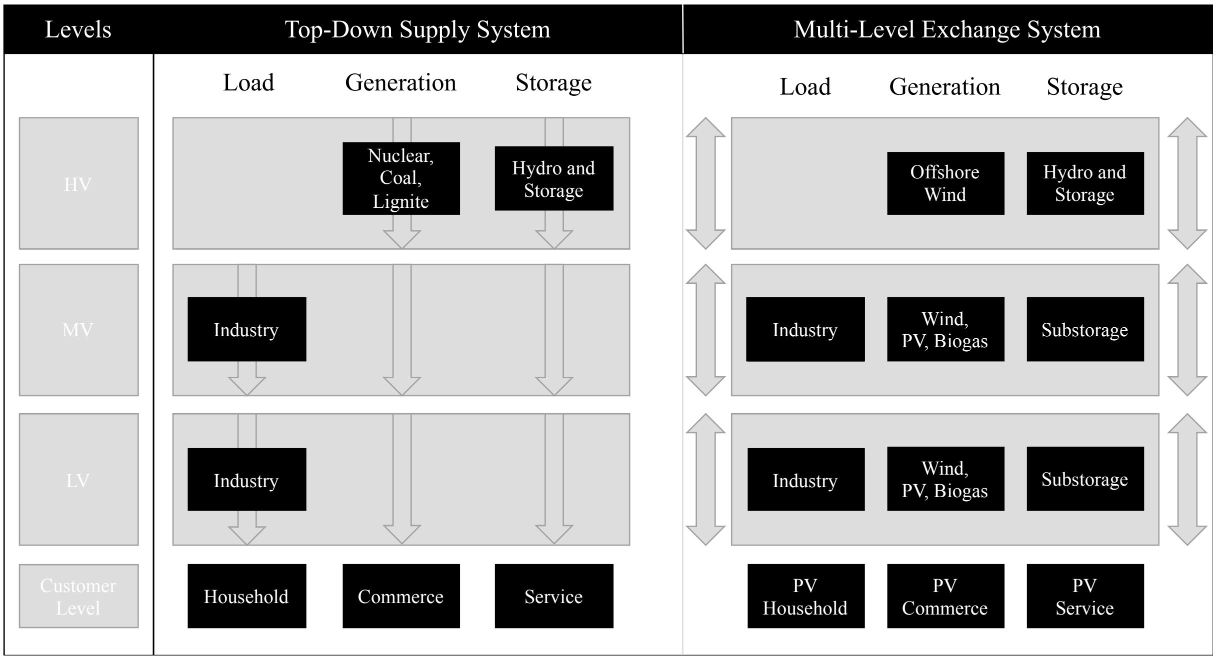

Figure 20: Transformation of the Electricity System [15]

The changes to the German energy system are a good example of a politically induced technological change process [16]. To get its citizens involved, the German government provided an incentive for the generation of electrical energy from privately owned PV panels with up to 0.507 € per feed-in kWh as regulated by the Erneuerbare-Energien-Gesetz (EEG –

Renewable Energy Law) [17, 18]. In addition, the government also introduced incentives for local storage systems, such as reduced interest rates for loans when investing in battery systems, to ensure a reliable energy source and rules for self-consumption to relieve the grid [5]. In this vein, we also take into account different discount rates for investments in the generation of electricity from renewable resources [19, 20]. These incentives for the generation of local electricity, storage and self-consumption support a bottom-up model for the energy transition and create the need for integrated intelligent management systems and customer obligation. Thereby, the reward for self-consumption is implicit in its nature. Consumers who consume their self-produced electricity do not have to buy it from the electricity supplier. Hence, the consumer saves 0.29 € per kWh, which is higher than the remuneration of the net feed-in tariff of 0.12 €/kWh. This leads to an overall saving through self-consumption of 0.17 €/kWh (0.29 €/kWh – 0.12 €/kWh). Figure 21 shows those areas which require new management structures [14]. These New structures could also be implemented on the low-voltage level. Prosumers can offer (part of) the needed storage and generation capacities. By relocating the generation of electricity, a relocation of the corresponding electricity services is also required. Thus, the need for new electricity services will increase with a growing share of RES, whereas the conventional generators who delivered most of the energy in the past will disappear. Thus, the decentralised generation entities have to be integrated into the energy system. Figure 21 indicates which areas of the electricity grid are affected and, in particular, which special services are required for relocation towards decentralized and small entities, such as prosumers.

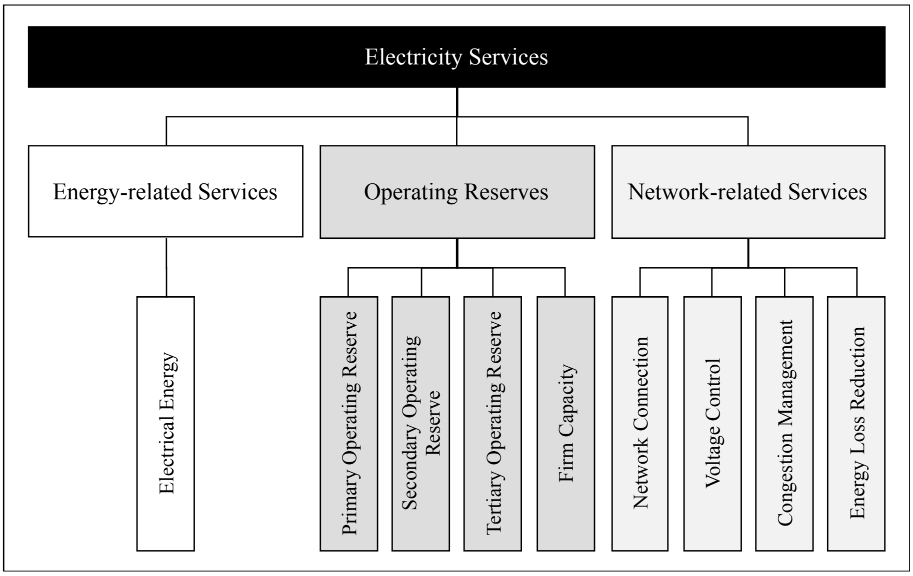

Figure 21: Electricity Services [14]

Due to governmental subsidies and as Figure 22 shows, installed PV power rose dramatically from 2000 to 2016 [21] even though installing a PV system comes with high initial costs [14].

These costs can mainly be attributed to investment costs as planning and approval costs are very low in Germany. Subsidised PV systems generate revenues over time. Even when incentives, such as guaranteed feed-in remunerations, are lower, investing in PV panels can still be attractive due to the opportunity to consume self-produced electricity, meaning that electricity does not have to be purchased with an average price of 0.2916 €/kWh (based on 3,500 kWh per year consumption [22, 23]).

Most of the savings of self-produced electrical energy result from the elimination of costs for distribution, levies and taxes. These are taxes (55%) and network charges (25.7%) but also surcharges for purchase and distribution (19.3%) [22]. Furthermore, fees for grid stability and ancillary services can be avoided [24].

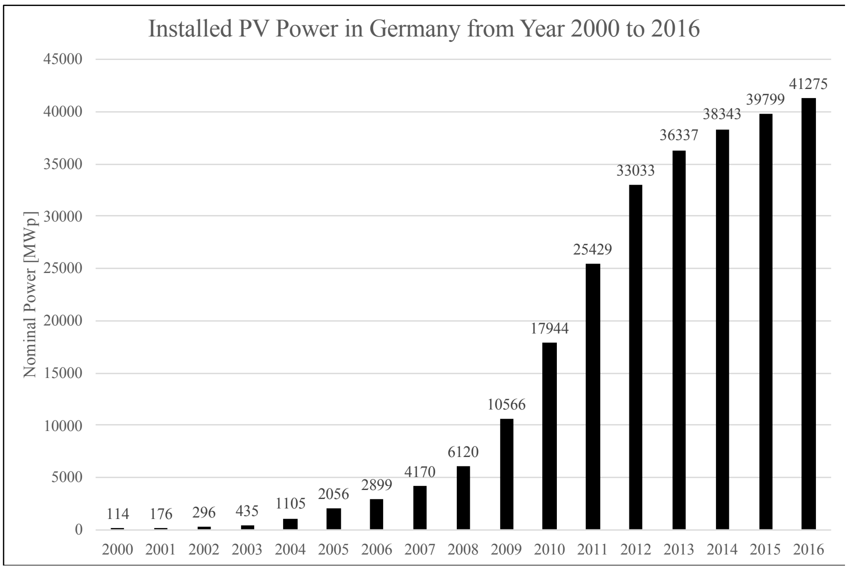

Figure 22: Installed PV Power in Germany from 2000 to 2016

The goal of this paper is to determine the financial feasibility of privately owned PV-based electricity generation under the specific market conditions in Germany and by considering the capacities of PV systems. “Specific market conditions” refers to electricity prices and, in particular, to feed-in tariffs and regulations. Regarding household electricity prices, Germany’s are the highest in Europe [25]. Regarding the feed-in tariffs and regulations, there are numerous variations in Europe [26]. Germany has a relatively high feed-in tariff, which is guaranteed over a time period of 20 years for private investors in PV panels. We worked with real data (so called H0 standard load profile) for an average German household and the data set of global radiation for Aachen (a city in western Germany) to calculate PV-based electricity production. In terms of PV system attractiveness Aachen is similar to many other cities in Germany because of its latitude and because of global radiation it is in the medium range within Germany. Furthermore, we calculated the economic feasibility of storage systems by taking the subsidised German feed-in tariff, market prices for battery energy storage systems (BES systems) as well as for PV panels, and an average electricity price of 0.29 €/kWh into account. Since the electricity price is largely made up of taxes and levies, the variable share of the generation cost per kWh is relatively small. Following that, the variances for the average electricity price is low.

With different scenario analyses, we computed the hourly electricity production, self-consumption, battery charge status and grid balance. Based on these values we determined the relevant cash flows. The net present value (NPV) and the resulting annuity were calculated using a total cost of ownership (TCO) model for 20 years, covering the typical usage period for PV panels in Germany. As mentioned, we used the H0 profile as our underlying consumption pattern of private households. Although it can be stated that a smart use of electricity within the household can increase the self-sufficiency rate or the efficiency of energy use [27], behavioural studies show that consumers do not always react rationally [28–30]. Hence, the H0 profile aims to realistically reflect current consumption patterns.

2.1.2 Literature Review

Existing literature has already analysed BES for private entities. Owing to the widespread challenges that the so-called prosumer model generates, the structured investigation of the different model options and the analysis of their economic feasibility appear to be necessary. To calculate the profitability of an integrated PV-BES-system, one should consider as many aspects as possible. Table 3 includes an overview of the relevant literature which has analysed the different perspectives of the prosumer model for private customers. We have also analysed papers which consider PV- and PV-BES-systems from a financial perspective. Table 3 and Table 4 show the methods and the assumptions made to generate viable results. In Table 4, we only list such papers which provide explicit values. However, no comprehensive approaches have been implemented yet. Therefore, in this article we go beyond the currently available literature and combine a PV and a BES, while also taking into account technical restrictions and evaluating the system from a financial point of view by applying a prosumer-oriented TCO model (TCO_P).

#	References	Business Adminis-tration		Economic	Technical	PV	BES	Description
		other	TCO					
1	Akter. Mahmud, and Oo 2017 [31]	x			x	x	x	• solar photovoltaic units and battery energy storage systems • levelised cost of energy along with reductions in carbon dioxide emissions and grid independency • in Australia
2	Bertolini, D'Alpaos, and Moretto 2016 [32]	x	x			x		• impact of a PV system for micro-grids
3	Bortolini, Gamberi, and Graziani 2014 [33]	x				x	x	• economic model for grid-connected PV and BES system in Italy
4	Comello and Reichelstein 2016 [34]	x				x		• economic efficiency of PV in the U.S. • remuneration system
5	Cucchiella, D'Adamo, and Gastaldi 2016 [35]	x				x	x	• profitability of PV systems • profitability of energy storage in a mature market in Italy
6	Kamankesh and Agelidis 2017 [36]	x		x		x		• optimising the management of the grid with high share of RES and V2G
7	Kaschub, Jochem, and Fichtner 2016 [37]	x				x	x	• developments of battery storage technology with PV • generation mix of utilities, use of the distribution grid, and electricity price
8	Klise, Johnson, and Adomatis 2013 [38]	x	x			x		• TCO for PV systems in the U.S. • discounted cash flow
9	McDowall 2017 [39]				x	x	x	• significance of BES for the autarchy of micro-grids
10	Naumann et al. 2015 [40]	x			x		x	• costs and revenues for BES • techno-economic model for revenues
11	Rosen and Madlener 2016 [41]			x				• changes in market regulations • enable trading of energy for prosumers
12	Rylatt et al. 2013 [42]			x	x			• market model • prosumer is embedded in an aggregator structure
13	Uddin et al. 2017 [43]	x				x	x	• photovoltaic systems integrated with lithium-ion BES • in UK
14	Vosoogh et al. 2014 [44]	x		x	x	x	x	• optimising the energy flow in a micro-grid
15	Zhang et al. 2016 [45]	x				x	x	• three different types of BES • in Sweden

Table 3: Prosumer Literature Review

#	Author	Interest Rate per Year [%]	Opportunity Costs of Capital [%]	Inflation per Year [%]	Electricity Price [ct/kWh]	Feed-in Remuneration [ct/kWh]	Lifetime PV [years]	Lifetime BES [years]
1	Akter. Mahmud, and Oo 2017 [31]	4	-	-	22	-	25	10
2	Bertolini, D'Alpaos, and Moretto 2016 [32]	5			16		20 and 25	-
3	Bortolini, Gamberi, and Graziani 2014 [33]	-	5	3	20	4	25	25
4	Comello and Reichelstein 2016 [34]	7.5			10 – 13.5	11 - 28	30	-
5	Cucchiella, D'Adamo, and Gastaldi 2016 [35]	3	5	2	20	19	20	20
6	Kaschub, Jochem, and Fichtner 2016 [37]	1	-	2	29.5	3.5	20	20
7	Klise, Johnson, and Adomatis 2013 [38]				11.1		25	-
8	Naumann et al. 2015 [40]	4	-	2	30	12.56	20	12.5
9	Uddin et al. 2017 [43]	-	-	-	-	-	-	5
10	Zhang et al. 2016 [45]	-	-	-	-	-	25	25

Table 4: Data Analysis from the Literature

According to Table 3 and Table 4, in the existing literature there are various investigations in the fields of PV and BES and their financial aspects. However, some work is limited to the consideration of PV systems only [32, 34, 38]. Other research which also considers PV and BES models focusses on countries and markets outside Germany, such as Australia [31], Italy [33, 35], Sweden [45] and UK [43]. Moreover, previous studies usually only consider one single household size [37] or assume (partially) already installed systems [40]. Many studies work with linearized prices for assets and services, whereby such a procedure does not reflect exactly the conditions for a potential prosumer.

In addition to models from scientific studies, there is also software available which can be used to calculate the economic viability of various clean energy projects, such as RETScreen [46], which is produced by the Canadian government. There are some scientific publications that use this software for their investigations. However, a deeper analysis of this tool is not possible, since publications from recent years that disclose the concrete calculations of the underlying model are not available. Based on the existing research, our contribution is the following: In our model, we provide an improved granularity regarding input data such as generation and consumption profiles, and we use exact prices for assets and their financing as well. Furthermore, we have adapted our model to the regulatory conditions in Germany, and we calculate the annuities, which a prosumer can easily compare with his or her monthly payments.

To do this, the application of the TCO_P concept is very suitable. The TCO method analyses activities and related cash flows within an investment's useful lifetime [47]. It has a broad scope and also includes pre-purchase costs, for instance [48, 49]. This comprehensive approach distinguishes the TCO from other comparable methods [50].

To investigate a long-term investment such as in a PV-BES-system, the TCO concept is particularly suitable because it is designed to be activity-based and it informs the entity – in this case the prosumer who owns the PV-BES-system – about the economics of past, current and future decisions [48, 51]. Furthermore, the TCO concept is logical and easy to understand, especially as it focuses on the total cost of an investment [47]. TCO shifts the focus from the purchase cost to the total cost, and is therefore more suitable for making informed decisions [52]. This means that TCO is not only a purchasing tool but also a philosophy [48] which helps a purchaser to understand the real costs of buying a particular good from a particular supplier [47, 48]. In this case, the paper provides objective information for those customers who want to become prosumers by investing in a PV and/or a BES-system. Furthermore, the TCO concept allows the user to understand, analyse and manage the financial consequences of purchased items in a progressive and systematic way [47]. Specifically, the TCO method allows the user to consider such elements as order placement, research and qualification of suppliers, transportation, receiving, inspection, rejection, replacement, downtime caused by failure, disposal costs, etc. [48, 53]. Thus, the TCO concept displays more than just purchase prices, by considering the costs of the entire product-life, such as those related to service, quality, delivery, administration, communication, failure, maintenance and so on [53, 54]. Beyond that, the TCO approach takes into account the transaction costs [52]. However, as the TCO concept requires detailed accounting and costing data, the lack of readily available data might be a limitation [48]. Furthermore, the "TCO concept requires firms [or entities] to consider those activities that are causing them to incur costs. By analysing flows and activities within each process, a firm can identify which activities add value, and which do not" [47]. Hence, the user of TCO_P is the prosumer conceptualising the system s/he is willing to invest in [55]. As our TCO model considers not only costs but also revenues from a prosumer's perspective, we make a contribution by extending traditional consumer-oriented TCO models towards a prosumer-oriented TCO model. To address the identified research gap by applying the TCO_P concept, this paper raises the following research questions:

1st Research Question

Which adjustments need to be added to existing TCO models in combination with PV-BES-systems based on detailed real-world data sets and how can the TCO_P be calculated for different PV systems in combination with BES systems under different usage scenarios?

2nd Research Question

What is the most cost-effective option for a PV-BES-system from the user perspective under consideration of German market conditions and how are the results influenced by German legislation for feeding-in electricity from renewable energy sources?

2.1.3 Contribution

The article makes a contribution by providing a TCO_P model based on the existing literature, which closes the identified research gap, by providing a comprehensive consumer-oriented calculation of a PV-BES-system with real data and different realistic household sizes. This article positions the prosumer as the owner of the system at the centre of our analysis. The calculation provides a realistic outcome of the aspects of using self-produced electricity, storage and connection to the grid, presenting the opportunity to feed-in and use electrical energy. We developed a TCO_P model for a 20-year lifetime period under realistic usage conditions with the possibility to analyse changes in the discount rate, inflation, increasing energy efficiency, etc. Based on this, we applied the model to real market data. Thus, we obtained results for different constellations of household size, PV system capacities and BES capacities. Using discrete optimisation, we were able to determine the financially best constellation for different household sizes. We also relate the calculations' results to the corresponding self-sufficiency rates. Although our analyses focus on the German energy market, the development of the extended TCO_P methodology can also be adapted to other market conditions or restrictions. Answering the questions above contributes to a more independent and holistic economic evaluation of participating in the energy transition in Germany as a prosumer. Moreover, the results help to identify relevant improvement potential for governmental policy makers when setting incentives and for producers when designing prosumer-oriented products.

This article is structured as follows: Chapter 2.2 discusses the methodology and explains the data set with its core components and restrictions. Chapter 2.3 discusses the results of baseline scenarios under German market conditions. Furthermore, we validate the methodology and perform various scenario and sensitivity analyses in order to show the impacts of changes with the variables used. Chapter 2.4 concludes with the key results, a short discussion of the limitations and a discussion of future research potential.

2.2 Methods

2.2.1 Sample

Our analyses focus on domestic households – detached houses with one family per house in the German city of Aachen with roof surfaces that are suitable for the installation of a PV system. We considered different household sizes, ranging from one to four persons and determined the financially optimal combination of a PV system and a BES. We also accounted for the investment in a PV system without any BES as well as the waiver of both. Different sizes of a PV system up to an installed capacity of 10 kW_p were included in the analyses. Larger systems are typically too large for the roof of a detached house due to the area needed. Furthermore, only the private operators of plants up to this size benefit from the legally guaranteed fixed feed-in tariff.

In our study, households were equipped with various battery storage devices available for home use. Exact values and data are provided in the following sections. The data structure and calculations used in this study are illustrated in Figure 24.

2.2.2 Instrument

Our TCO_P calculations are based on a comprehensive model including all cash flows related to electricity consumption, generation and storage using a dynamic investment appraisal method – the Net Present Value (NPV) method. The basic structure of the calculation of the annuity calculation based on an investment's NPV is shown in Equation 1.

$$C_{TCO_P} = C_{NPV} \frac{(1+i)^t * i}{(1+i)^t - 1} \quad (1)$$

C_{TCO_P} characterises the annual prosumer-oriented total cost of ownership, hereinafter also referred to as annuity. C_{NPV} is the Net Present Value, t is the index for the period and i is the rate, with which all payments are discounted. The costs are considered on an annual basis, as costs per year are usually calculated in the private energy sector.

For the general structure of the TCO_P model, please refer to Figure 23.

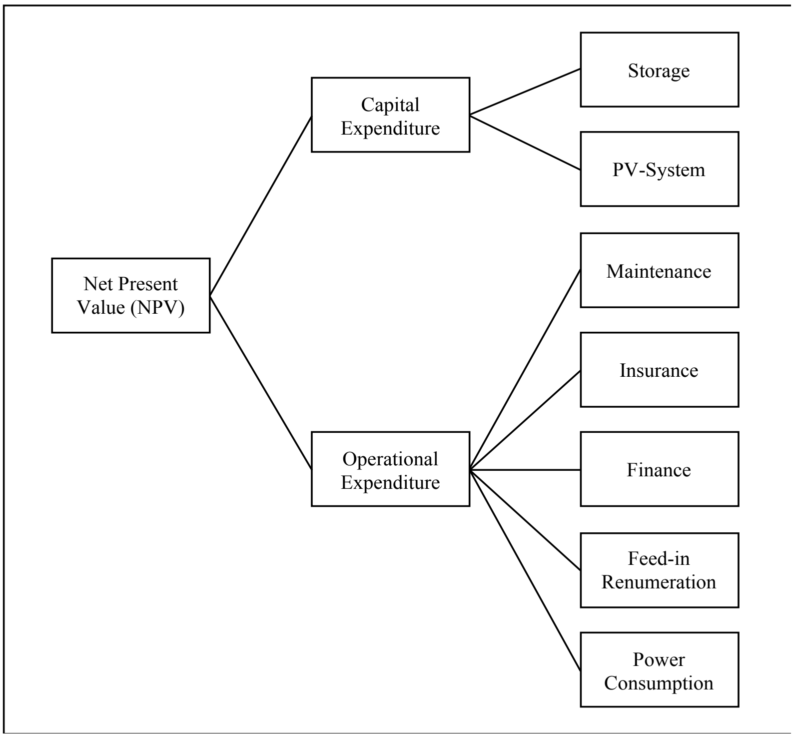

Figure 23: Structure of TCO_P Model

Our model was implemented using Visual Basics for Applications (VBA).

2.2.2.1 Net Present Value

The net present value C_{NPV} was determined by adding up all observed cash flows, which are discounted on an accrual basis, as shown in Equation 2.

$$C_{NPV} = C_{Capex} + \sum_{t=1}^{T} \frac{C_{Opex,t}}{(1+i)^t} \quad (2)$$

C_{Capex} is the capital expenditure, $C_{Opex,t}$ is the operational expenditure in period t, T is the whole period under review and i is the discount rate. The elements of C_{Capex} and $C_{Opex,t}$ are described in the following sections.

The NPV is calculated with different parameters: internal and external ones. The interdependencies are illustrated in Figure 24.

2.2.2.2 Capital Expenditure

The capital expenditure for the prosumer consists of two main components which have to be provided at the beginning of use. The first expenditure is for the PV panels, which are mounted on the roof of the house and generate electricity after installation from the available solar radiation. Moreover, the brackets that are used to position the panels on the roof, and the power electronics required for using the panel incur additional capital expenditure. Additionally, the one-time installation of the system should be taken into account as it entails a considerable part of the expenses.

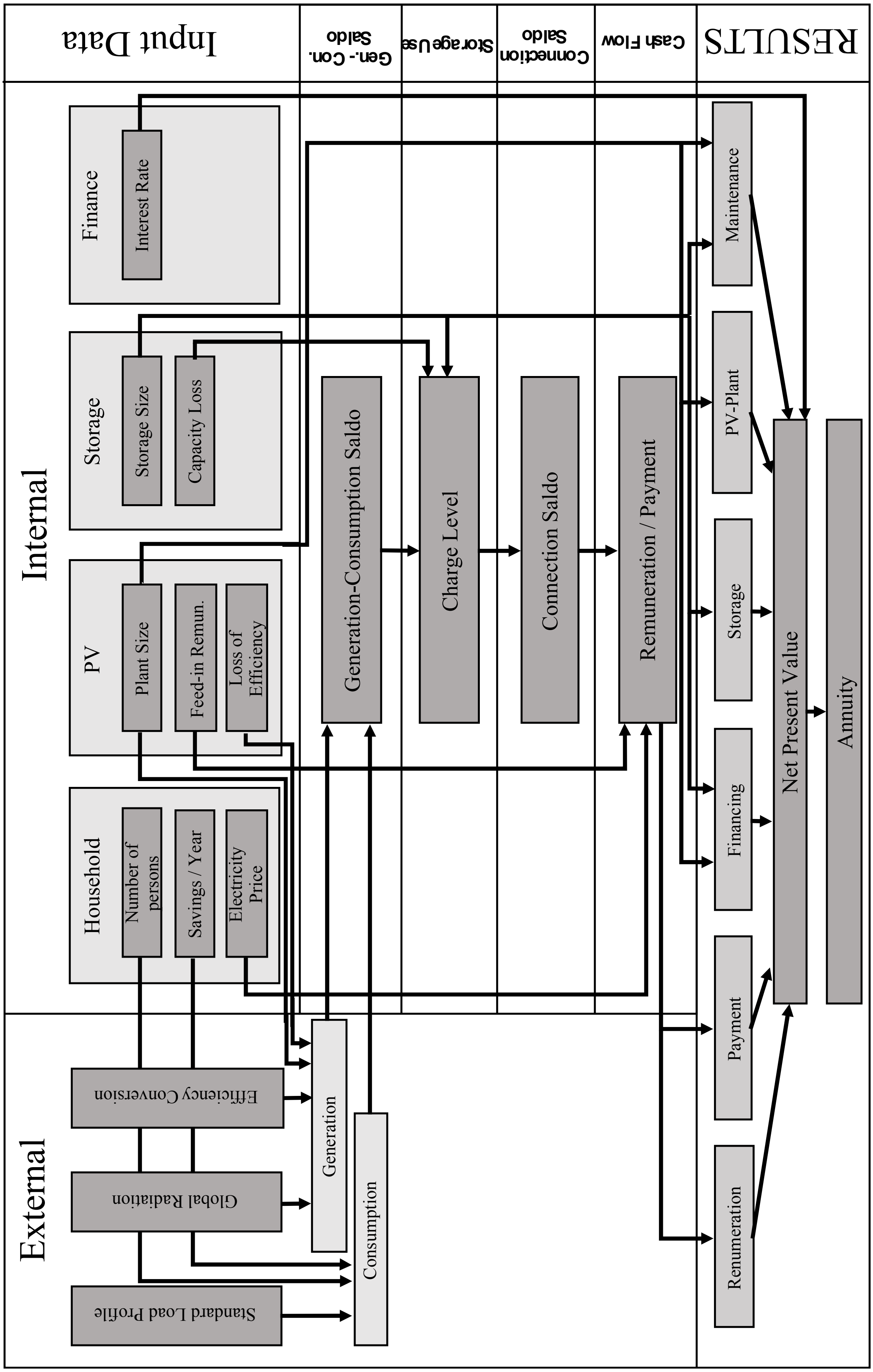

Figure 24: Data Structure

The second capital expenditure that has to be considered is for the battery storage. The battery storage can be purchased together with the PV system as a package or separately. For feed-in and current discharge, power electronics are needed as well. This battery storage can be seen as a separate investment, since it is optional and can be installed in addition to an existing PV system or simultaneously with a new PV system. It does not make sense to install a battery storage without a PV system because there is no financial advantage of feeding-in electricity that has been withdrawn from the grid before and it is not compensated by the EEG either. Another asset that has to be installed is the grid connection. However, all costs covering this investment have to be borne by the local distribution system operator (DSO). In Germany the local DSO is obligated by law to set up a grid connection for any renewable energy source [56]. The operator of the system only has to request that the necessary devices are set up.

Since we do not consider a 100% isolated system, a complete omission of an investment is also possible. In this case there is no capital expenditure, of course. Thus, the "traditional" consumer with a normal grid connection suitable for consumption can be seen as our base case. The Kreditanstalt für Wiederaufbau (KfW) bank offers special loans and federal subsidies for BES [57, 58] to finance the listed expenditures.

2.2.2.3 Operating Expenditure and Revenue

The operating expenditures are manifold. It is a fact that every consumer/prosumer has to pay for electricity that is drawn from the grid. As a private customer, a fixed price per kWh is paid to the respective electricity supplier. The amount of electricity drawn from the grid depends on various factors. Without PV panels and battery storage, all power consumption is drawn from the grid. If a PV system exists, electricity is only drawn if the current consumption in the household exceeds the current electricity generation of the PV system. If a battery storage is added, the purchase of electricity from the grid is limited to situations where both the consumption exceeds the generation and the battery storage is empty and can no longer provide electrical power.

This is (partially) offset by payments for electricity fed into the grid. Just like the price for the electricity consumed, the feed-in tariff is fixed at a certain amount per kWh. The payment is made by the grid operator and is guaranteed by the EEG. If no storage is available, electricity is fed into the grid as soon as the electricity generated by the PV system exceeds consumption. In combination with a BES, electricity is fed-in when both production exceeds consumption and the battery storage unit is fully charged and cannot store any more electrical energy.

Two other cost categories have to be considered. If a prosumer invests in both a PV system and a BES, then both have to be maintained and the PV panels are often insured against, for instance, damages caused by hail. Regardless of the operation, but still during the use phase, there are cash flows caused by financing the PV system and the battery storage. The payments include the repayment of the loan and the corresponding interest payments. The financing of the acquisition costs by means of a loan is not obligatory but it is recommended due to the aforementioned support from the KfW bank and the German Federal Government.

2.2.2.4 End-of-Life Costs

Our calculations do not consider end-of-life costs. Due to the fact that BES is a new technology, there is no reliable information available about potential revenues or costs associated with PV systems and battery storage systems at the end of their lifetime of 20 years. Therefore, we assume a cost-neutral disposal of the devices.

2.2.3 Parameter Values of Core Components

2.2.3.1 Capital Expenditure

To create a basis for our calculations, we initially collected data for the German market for battery storage systems for home use. The capacity of battery storage units available on the market ranges from 2 kWh [59] to 20 kWh [60]. BES are offered by different companies. On the one hand, there are automobile manufacturers, such as Mercedes-Benz [60] and the electric car manufacturer Tesla [61]. Furthermore, electronics manufacturers offer battery storage systems for household use. For example, copies of LG [62] or Samsung [63] are available. On the other hand, manufacturers such as sonnen GmbH [64] specialise exclusively in products related to private solar power.

We then manually collected data on the products of the various suppliers according to capacity and price to obtain a comprehensive overview of the German BES market. For all suppliers, the price per kWh of storage capacity decreases as the capacity of the battery storage increases. Based on our compilation, we calculated an average price of 1,250 € for 1 kWh of storage capacity. This price per kilowatt hour is somewhat higher for small storage systems and slightly lower for larger systems.

The market leader in Germany is the supplier sonnen GmbH with its products summarised under the brand name sonnenBatterie [65]. Batteries for households are on offer in all relevant sizes. Our market analysis shows that these products represent the market very well in terms of the relationship between the price and the performance offered. Based on our maxim of calculating with concrete, real market data in all areas, we chose models from their product portfolio for our research. Table 5 shows the different models used in this study [64]. These products are fully representative of the market both in terms of price to capacity ratio and in terms of the sizes on offer.

Capacity (kWh)	Brand	Price (incl. VAT)
6	sonnenBatterie	8,799 €
10	sonnenBatterie	12,799 €
16	sonnenBatterie	17,699 €

Table 5: Selected BES Models

The guaranteed minimum lifetime of the selected battery storage is 10 years. However, this does not mean that the battery memory is no longer functional after this period of time. Previous studies assume a total lifespan of 20 years or more [33, 35, 37, 45]. This corresponds to the period covered by our study. Thus, it would be worth using a battery storage during this observation period. In order to take the ageing of the battery storage into account, we tested our results for influences of an annual decrease in storage capacity (see chapter 2.3.3.3).

Prices for PV systems have fallen sharply over the past 10 years. High production figures have led to significant economies of scale, and the competitive pressure on the market has become increasingly powerful. In recent years, however, the decline in prices has slowed down [66]. Based on past data, we assume an average price of 1,168 € per kW_p of installed capacity. This includes the cost of installation and wiring. The size of the installed system cannot be chosen freely but depends on the number of installed panels, which is an integer number. As a representative example, we chose the panels of the German manufacturer Viessmann [67]. This company is one of the leading manufacturers of solar panels in Europe, and especially in Germany [68]. Table 6 shows the different variations of installed capacity used in this study. The listed panels are fully representative of the market in terms of technical parameters and the ratio of price and nominal capacity.

Installed capacity (kW_p)	Brand	Number of panels	Price (incl. installation and wiring; VAT)	Covered roof area (m^2)
4.88	Viessmann	16	5,699.84 €	26.08
7.32	Viessmann	24	8,549.76 €	39.12
9.76	Viessmann	32	11,399.68 €	52.16

Table 6: Selected PV Models

The guaranteed lifetime of the chosen PV panels is 25 years. The manufacturer guarantees at least 80% of the original nominal capacity for the first 25 years [67]. In our study, we assumed that the PV panels are installed once and then used for the whole observation period of 20 years. This is consistent with previous studies, all of which assumed a lifetime of 20 years or longer for PV panels [31, 33, 35, 37, 40, 45]. In addition, the legally guaranteed remuneration period amounts to 20 years [69]. Losses of nominal capacity of the PV panels are taken into account by testing our results for influences of different yearly losses in efficiency (see chapter 2.3.3.2).

2.2.3.2 Operating Expenditure and Revenue

The expenditures for operating a prosumer system can be divided into fixed and variable costs. Fixed costs are costs for maintenance and insurance. Both values can vary depending on the data source. Some providers of systems include maintenance and/or insurance in the price. Therefore, some studies have calculated these costs as a proportion of the investment costs. However, it is usually common for maintenance and insurance to be paid annually. On the basis of various offers on the market and work from previous studies, we assumed that 100 € per year will be spent on maintenance and 70 € per year on insurance [33, 35, 40]. For example, the functionality of a PV system and the associated electronics must be checked regularly. The variable costs result from the consumption of the electricity drawn from the grid. These are partially offset by the revenues from feeding the self-generated electricity into the grid.

To determine a representative consumption profile, we received information from the local DSO “Regionetz” [70]. This information provides a curve of the electricity consumption of a typical household in Aachen on a quarter-hourly basis. With this curve and the average annual consumption of different household sizes, the consumption values are calculated in quarter-hourly cycles over the course of a whole year. Changes in consumption quantity were taken into account in the scenario analysis discussed in chapter 2.3.3.

To calculate the electricity generated by the PV panels, we adopted an approach that provides the most realistic possible data basis. Global radiation causes the production of electricity with PV panels. This global radiation varies depending on the location and the position of the sun as well as the weather. A PV system with an installed capacity of 1 kW_p at the Aachen site generates 883.5 kWh of electricity per year on average [71]. This value already includes efficiency losses due to temperature fluctuations, line losses and power electronics. The amount of electricity generated can vary slightly within Germany but differences in most areas within Germany are relatively low compared to other countries. The reason for this is that in Germany a large part of the global radiation is diffuse radiation. Diffuse radiation also occurs under cloudy conditions and is less dependent on the exact position of the sun [72, 73].

In order to obtain a representative generation profile, measured values for global radiation for the years 2011-2017 for the Aachen site [73] were used. Together with the average electricity generation, we were able to calculate annual generation profiles with an hourly resolution which we divided linearly into quarter-hour sections. This approach allows us to reach the lowest granularity possible even if we should lose a small amount of accuracy due to the unavailability of more detailed data coverage on electricity generation.

Combining both consumption and generation allows the difference between electricity generation and consumption to be calculated. A positive difference indicates that generation exceeds consumption, whereas a negative difference is indicative of the opposite. For a positive difference, the excess electricity is fed into the grid or the battery storage is charged. If the difference is negative, electricity is withdrawn from the grid or from the battery storage.

Without any battery storage, no further decision is required. However, if there is a battery storage, the prosumer has to decide between feeding-in and charging or, rather, between withdrawing from the grid and withdrawing from the battery storage. As the feed-in remuneration is significantly lower than the price of electricity from the grid, the financially best option is always to charge or to discharge the battery storage until it is fully loaded or fully discharged before feeding-in or withdrawing, respectively.

In accordance with this strategy, we map a curve showing the charging level of the battery storage and a data series of feeding-in and withdrawal activities. Those streams of electricity, both the fed-in and the withdrawn electricity, can be assessed financially. Charging and discharging the battery are not linked to any cash flows. For electricity withdrawn from the grid, we used a price of 0.29 €/kWh according to the average price of electricity for private consumers in Germany [74]. The feed-in remuneration for private households with a PV system up to 10 kW_p is guaranteed by law and amounts to 0.12 €/kWh [56]. A combination of feeding-in and withdrawing electricity with the mentioned prices yields the respective cash flows. Changes in the remuneration tariffs and the price for withdrawn electricity are taken into account for the scenario discussed in chapters 2.3.2.1 and 2.3.3.5.

The cash flows caused by financing are calculated on the basis of the financing program of the German KfW for PV systems and battery storages. The whole system is financed with a credit period of 10 years and an interest rate of 2.5% [57]. Subsidies provided by the Federal Government of Germany support the repayment of the loan depending on the size of the installed system [58]. Since this type of financing is a condition for the federal repayment subsidies, which reduce the financial burden on the prosumer, the payment structure resulting from financing must be considered.

2.3 Results and Discussions

2.3.1 Baseline Scenario with German Market Conditions

In this chapter, we present the main results of our calculations based on data presented in previous chapters as input for parameters (baseline scenario). As described before, we look for the best constellation of PV and BES from a financial point of view for private households with 1 to 4 persons. Our results for all possible constellations are shown in the following figures. For every household size and every considered PV system ("Basis" stands for no PV system and hence no battery storage system installed), the annuity depending on the used battery size is shown in Figure 25.

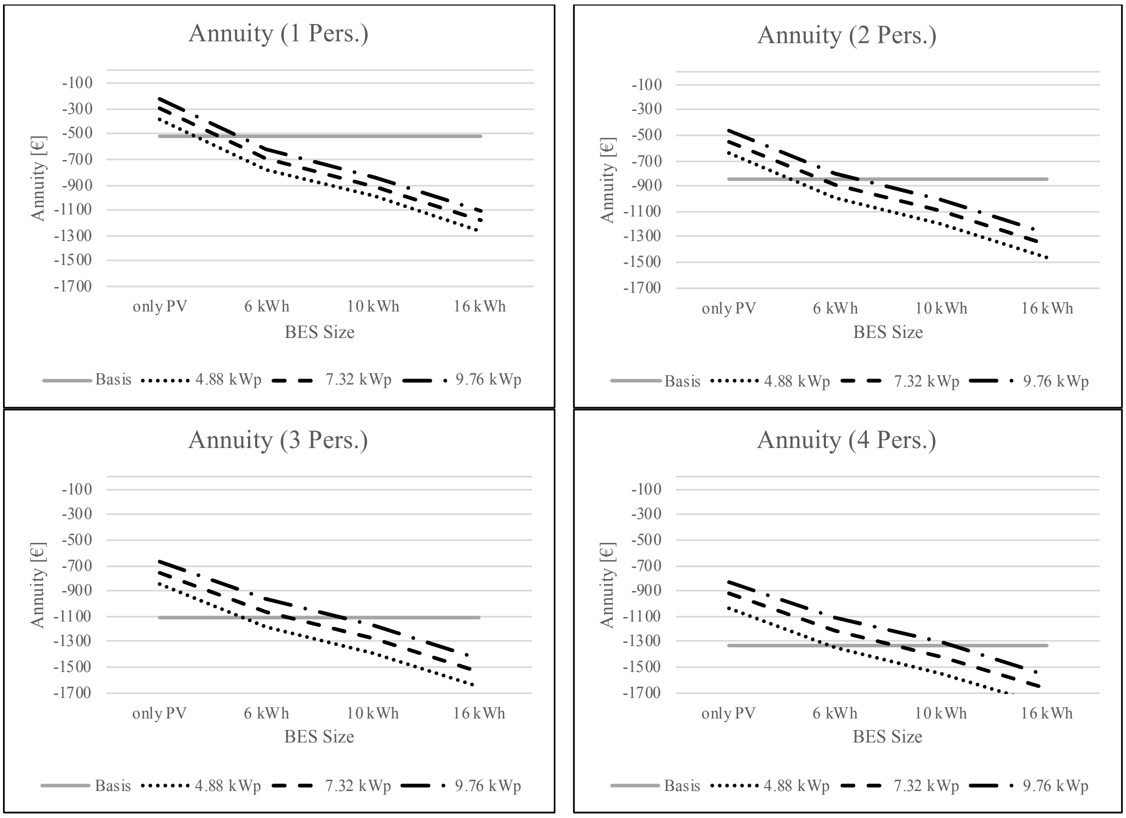

Figure 25: Results Baseline Scenario

The first insight that can be gained from our results is that the benefits of the individual constellations are very similar across all household sizes. As for the size of the PV system to be selected, the following can be stated: Regardless of all other sizes, a larger PV system is always financially more advantageous than a smaller system. Consequently, the first decision rule can already be derived for private consumers: If roof area is available, then this area should be used as much as possible for the installation of as many PV panels as possible. The only restriction is the legal cap of 10 kW_p for unlimited remuneration for electricity fed into the grid. Looking not only at PV systems but also at the financial impact of the use of battery storage systems, the results are also clear. According to our calculations, the use of battery storage in all constellations impairs the financial result for the decision-maker. This is irrespective of the household size and the selected size of the PV system. Hence, the financially best alternative is always not to use any battery storage system.

From these findings, the financially optimal decision can be formulated as a simple rule. For all four household sizes, the constellation of no battery storage system and a 9.76 kW_p PV system represents the financial optimum. For a 4-person household we calculated an annuity of -828.44 € with this constellation. If this kind of PV system cannot be completely installed due to external circumstances, any PV system size without a battery storage system is financially more advantageous than the scenario “Basis”, where all of the electricity required is drawn from the grid and which leads to an annuity of -1,323.84 € for a 4-person household. Therefore, potential savings of -495.40 € per year can be achieved for this household size.

As mentioned above, any use of battery storage systems reduces the NPV and the related annuity of the total investment. For a one-person household, even with a 6 kWh battery storage system, the annuity is worse than the “Basis” scenario, regardless of the selected size of the PV system. We calculated an annuity of -511.97 € for the “Basis” scenario and -622.19 € for a 6 kWh battery storage system and a 9.76 kW_p PV system. For the other household sizes, the smallest battery storage size was even better for larger PV systems than for the "Basis" scenario. However, the larger battery storage systems are not financially advantageous.

Although battery storage systems do not offer any financial advantages, they can significantly increase the self-sufficiency rate of a household. The degree of self-sufficiency indicates the share of self-produced electricity in total consumption. While this value is in the range of 40-50% when a PV system is used alone, it increases to as much as 95% in a single-person household when the smallest battery storage (6 kWh) is used. Even 77% can be achieved in a 4-person household. Obviously, in the “Basis” scenario there is a self-sufficiency rate of 0%. In addition to this considerable increase, it is still remarkable that a further increase in the size of the battery storage system does not result in a further significant increase in the self-sufficiency rate. The number of days on which a larger capacity of the battery storage system is fully utilised is very small. For more detailed results, please refer to Table 8 in the appendix.

2.3.2 Baseline Scenario with Altered Selected Parameters

As can be seen in the different capacity constellations, there are some solutions which create value from the financial perspective and others which do not. This is an important result for the transition of the German energy system and the respective incentives set by policy makers. On the one hand, we have to consider the falling feed-in tariffs. Since the first EEG energy law, the guaranteed remuneration has been lowered from 0.507 €/kWh in 2004 to 0.12 €/kWh in 2018 for small PV systems. A scenario discussed by politicians is the total abolition of guaranteed remuneration subsidies in the future (only relevant for newly installed PV systems). As a result, guaranteed fixed feed-in tariffs for small systems would be cancelled and even the electricity from smaller PV systems would have to be traded on national or local markets. However, even in this case, positive prices for electricity of about 0.03 €/kWh to 0.05 €/kWh [75] could be expected (even when opportunity revenues from self-consumption are not taken into account). On the other hand, the highest share of the investments in the given scenario is driven by the price of the BES. However, prices for chemical energy storage systems are decreasing heavily. Hence, we investigated the sensitivity to lower battery prices per kWh. The following sections discuss these variations in feed-in tariffs and the prices of battery storage systems. Table 7 presents the chosen scenarios, detailed data can be found in Table 9 and Table 10. With the chosen household sizes, we cover over 95% of German households [76]. Furthermore, the different sizes of PV systems represent the full range of systems investigated in this paper.

	Scenario 1	**Scenario 2**	**Scenario 3**
Number of persons	1	2	4
Energy consumption per year [kWh]	1,714	2,812	4,432
Size of PV system [kW_p]	4.88	7.32	9.78

Table 7: Overview of the Scenarios Implemented

2.3.2.1 Flexible Feed-in Tariff

As mentioned above, the guaranteed feed-in tariff in Germany was set by law to 0.507 €/kWh for small PV systems with the first EEG energy law in 2004. The subsidies have been increasingly reduced to 0.12 €/kWh today. In the medium-term, electrical energy produced from renewable sources will have to compete under market conditions with the current market price being about 0.04 €/kWh on the daily market [74, 75]. Hence, we calculated scenarios where we vary different feed-in tariffs from the maximum of 0.507 €/kWh to today’s market price of 0.04 €/kWh. Considering the mentioned bandwidth, we show relative changes in attractiveness due to former developments and possible future progress. Figure 26 shows three selected scenarios with the variation of the battery storage capacity corresponding to different household sizes.

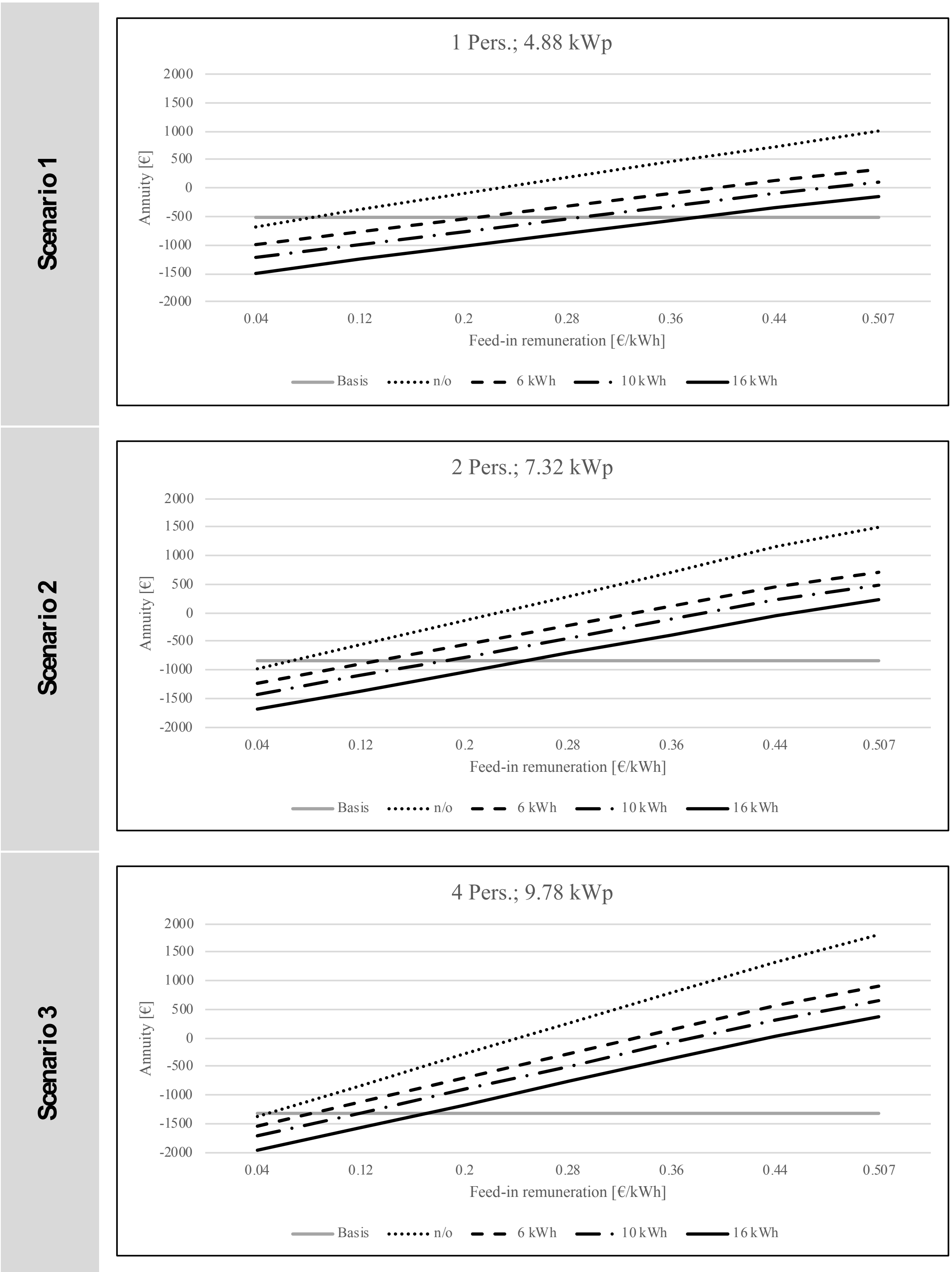

Figure 26: Results Flexible Feed-in Tariff

As Figure 26 depicts, the results vary. While the horizontal lines show the annuity without any PV-BES-System, it can be seen that the German stock market price generates no added value in comparison to the consumer model ("Basis" scenario). Even with today's guaranteed remuneration, owning a battery only makes financial sense in a few cases with the combinations mentioned compared to the corresponding “Basis” scenario.

On the other hand, the graphs show that larger PV systems are more profitable when consumption rises. The larger batteries do not have a greater financial benefit than the smaller ones.

Not surprisingly, the financial benefit of a combined PV-BES-system is generally better with higher remuneration fees. In addition, the purchase prices for batteries are very high, which decreases the annuity of the system. As a result, the PV system (without BES) is the most profitable combination from all of the considered variations. Although batteries increase the self-sufficiency rate dramatically from 47.37% up to 88.16% − according to our calculations in scenario 1, there is no financial benefit with the current market prices of BES. However, the financial attractiveness of battery systems changes significantly if the feed-in tariffs exceed a critical value. For small households, this is the case at just under 0.40 €/kWh and for large households it is already the case at less than 0.20 €/kWh. With the historical feed-in tariffs of over 0.507 €/kWh, an investment in such a battery system would always make sense financially.

2.3.2.2 Flexible Battery Price

The prices for battery storage systems need to change if an investment in them is to have a financial advantage. Since the purchase prices for batteries have decreased dramatically in the last decade and the assumption is that this trend will continue, it is reasonable to vary the different purchase prices for batteries in the given scenarios [77].

If the price decreased from 400 €/kWh in 2013 to a forecasted 108 €/kWh in 2020, the decreasing rate would be about 10% per year and kWh [77]. Hence, the benefit of the calculated PV-BES-System would increase with each year. Figure 27 provides the results for the three selected scenarios that range from a low consumption with a small PV system to a high consumption with a large PV system, showing different battery options and considering different purchase prices.

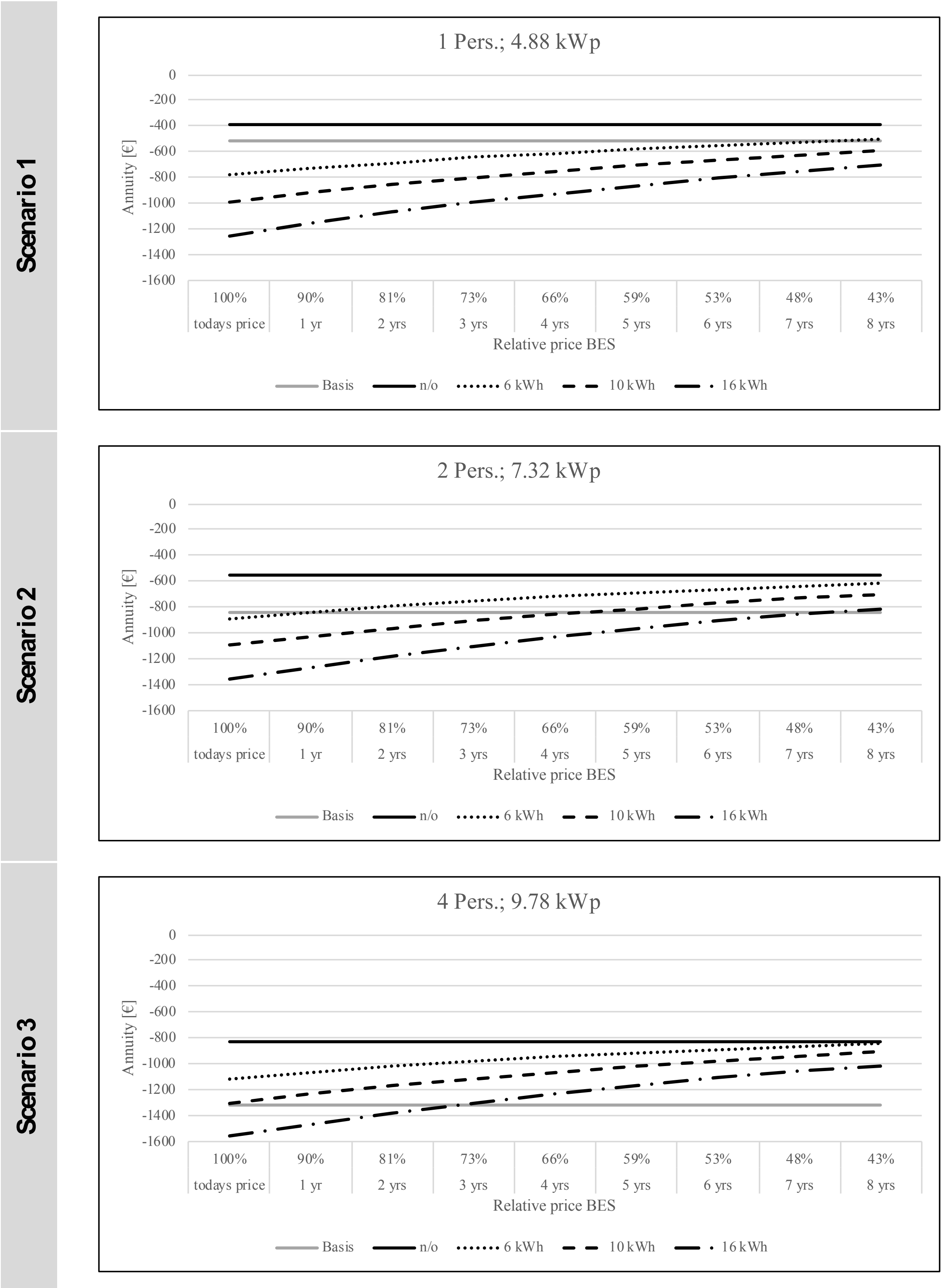

Figure 27: Results Flexible Battery Price

The two horizontal lines represent the “Basis” scenario (grey) without any PV system or BES and the PV-only scenario (black). Obviously, the battery price does not influence these scenarios. The other graphs show the different battery options in the scenarios. According to our calculations, the purchase price of the battery has a huge impact on the annuity of the PV-BES-system.

In the one-person household scenario, investment in a PV system has a positive impact on the annuity (-387.24 € as opposed to -511.97 €). However, batteries in a small system, with low consumption and generation rate, do not have a positive financial impact (-776.95 € and below).

In the two-person household scenario, again it is most profitable to only invest in a PV system (-547.94 €). Compared to the current consumer scenario (without PV and/or BES; annuity of -839.94 €) a 10% decrease in the battery price is sufficient for the PV-BES-system to be profitable for the small battery (6 kWh), which leads to an annuity of -839.92 €. However, the large battery will only be profitable (annuity of -840.30 €) if the price is decreased by about 57%.

In the four-person household scenario, we can see the higher profitability of the PV-BES-system with small (6 kWh; annuity of -1,113.96 €) or medium (10 kWh; annuity of -1,307.67 €) BES compared to the current consumer scenario, which has an annuity of -1,323.84 €. If the purchase price is decreased by one third, the large PV-BES-system will also have an annuity of -1,307.67 € and become more profitable than the current consumer model.

Overall, it can be stated that an investment in a PV system is financially profitable in all scenarios compared to the "Basis" scenario. Furthermore, the profitability of the PV-BES-scenarios increases with falling battery prices. Even if a combined PV-BES-system will always increase the autarchy of the prosumer, no scenario with BES proves to be more profitable than the PV-only system − even if battery prices decrease by up to 57 percent. One explanation for this is the high purchase price for BES. On the other hand, the small units and small margins of electrical energy do not compensate the BES investment. This result is also driven by the fact that the full range of the battery is only used for a few days a year.

Finally, the battery price has a huge impact on the annuity of the system and can make the difference as to whether it is profitable or not. Assuming falling battery prices, some scenarios will become more profitable than others. However, if there is no focus on autarchy, investing only in PV panels without installing a battery the most profitable investment in all considered scenarios. This could change if the BES is used more flexibly, e.g. by adding a heating pump or a smart charging wall box for EVs to the system. With an increasing use of storage, its value will increase potentially.

2.3.3 Sensitivity Analysis

As described in chapter 2.2, our calculations are based on a large number of input variables, all of which have an influence on the results. Some figures are subject to different uncertainties which cannot yet be completely eliminated. In order to estimate and assess the impact of these uncertainties, we have conducted various sensitivity analyses. Having examined the influence of changes in feed-in tariffs and the prices for battery storage systems in the previous chapter, we outline below the energy efficiency of households, efficiency losses of the PV system, capacity losses of the battery storage system, internal discount rates and developments in the price of electricity withdrawn from the grid. We have chosen the same three scenarios as in the previous subchapter (see Table 7) to be compared with their corresponding “Basis” scenarios in order to create a meaningful overview. Figure 28 presents the observed scenarios, detailed data can be found in Table 11 to Table 15.

2.3.3.1 Case 1 – Energy Efficiency of Domestic Households

In our calculations we assumed that the electricity consumption of the various household sizes will not change over time. So far, improvements in the energy efficiency of individual appliances and the increasing number and size of appliances consuming electricity in private households have largely offset each other. Nevertheless, in order to carry out a comprehensive review, we examined annual savings in electricity consumption of up to 3% in our sensitivity analysis in order to meet the requirements of the EU commission [78].

As a result, an increasing annual saving in electricity consumption influences the NPV and the annuity in such a way that both of them increase. However, the corresponding graphs show that the impact is small and, above all, that there are hardly any differences between the selected scenarios and the corresponding "Basis" scenarios.

For example, for a household with one person, an increase in the annual efficiency of 3% leads to an improvement of 21.7% in the annuity of the “Basis” scenario, while the annuity of the reference scenario (4.88 kW_p; no BES) improves by 21.5%. Therefore, a significant influence of this input variable on the financial advantage of individual constellations is not given.

2.3.3.2 Case 2 – Efficiency Losses of the PV System

In our calculations we assumed that the capacity of the installed PV system is completely available over the entire period under consideration. This assumption can also be challenged or must be validated to the extent that the effects of a deterioration in installed capacity on the overall results are examined in a sensitivity analysis. We consider annual losses of up to 2% in the available capacity of the PV system [79].

Obviously, the result in the "Basis" scenario is not affected. However, the NPVs and the respective annuities of the reference scenarios fall due to the increasing demand for electricity drawn from the grid. For example, for a household with two persons, the annuity of the reference scenario (7.32 kW_p; 6 kWh) decreases by 15.3% when considering annual efficiency losses of the PV system of 2% instead of 0%. Nevertheless, there are no decisive shifts in the benefits in this case either.

2.3.3.3 Case 3 – Capacity Loss of the BES System

In our calculations we assumed that the available capacity of the battery storage systems will not be reduced. Due to a lack of experience to date, reliable values for capacity-losses over time are difficult to predict and the only indication is the guarantee provided by various manufacturers (e.g. [80]) that after 10 years at least 80% of the original storage capacity will still be available (compare also [45]). To get an idea of the financial impact of potential capacity losses of the BES system, we examined the effects of an annual capacity loss of up to 2% in a sensitivity analysis. Over the entire 20-year period under consideration, this would correspond to a loss of 33.2% of the capacity initially available.

Consequently, this manipulation does not change the results of the "Basis" scenarios (no PV, no battery storage system). In the reference scenarios, the annuity deteriorates due to a decreasing proportion of the self-used electricity drawn from the BES system. The financial changes of our results are negligibly small. The difference of the annuity for a household with four persons amounts to only 0.4% in the relevant reference scenario (9.78 kW_p; 10 kWh). There is no influence on the financial advantage of decision alternatives.

2.3.3.4 Case 4 – Discount Rates

Another factor that is examined with regard to its influence on the financial results of our calculations is the internal discount rate that is used in calculating the NPV for discounting the single cash flows. Depending on the private decision-maker's wealth, financing alternatives and preferences for current and future consumption, the discount rate that is applied can vary. For the baseline model, we used a discount rate of 3%, which we varied from 0 to 5%. These assumptions are reasonable if we consider the current interest rates in Germany to be in line with assumptions made in other papers (see Table 4).

As all scenarios are characterised by series of payments, which are discounted in our model, all scenarios are affected by varied discount rates. In the "Basis" scenarios, the changes that occur are small. In the reference scenarios, the NPV decreases as the internal discount rate rises. When, for example, considering a household with two persons, a change in the discount rate from 3% to 0%, improves the annuity by 1.9% in the "Basis" scenario, while there is an improvement of 18.1% in the reference scenario (7.32 kW_p; 6 kWh). However, within the analysed range of changes to the discount rate, there is no change to the financial advantages of decision alternatives.

2.3.3.5 Case 5 – Electricity Price Inflation

Our calculations assume that electricity prices will remain constant. Future developments of this influencing factor are subject to great uncertainties. The strong price increases in Germany over recent years were primarily due to the increasing share of renewable energies and the introduction of the EEG levy. In our sensitivity analysis, we examined annual price increases of up to 6%, which is higher than the literature assumes (see Table 4).

Electricity price increases have a particularly strong influence on the "Basis" scenarios, but it should be noted that an annual increase of 3.53% would lead to a doubling during our observation period. Since the electricity prices for private consumers have been constant over the last four years [81, 82], we also took this fact into account in our case. In this respect, there are no shifts in the financial advantage. For example, comparing inflation rates for electricity prices of 0% and of 3% shows that for a household of four persons, the annuity of the "Basis" scenario decreases by 30.5%, whereas the annuity of the reference scenario (9.78 kW_p; 10 kWh) decreases by only 5.7%.

The results show that the access to a BES system can minimize the risks of increasing prices for electricity. Even in the case of a 6% price inflation, the overall annuity for all scenarios only diminishes slightly.

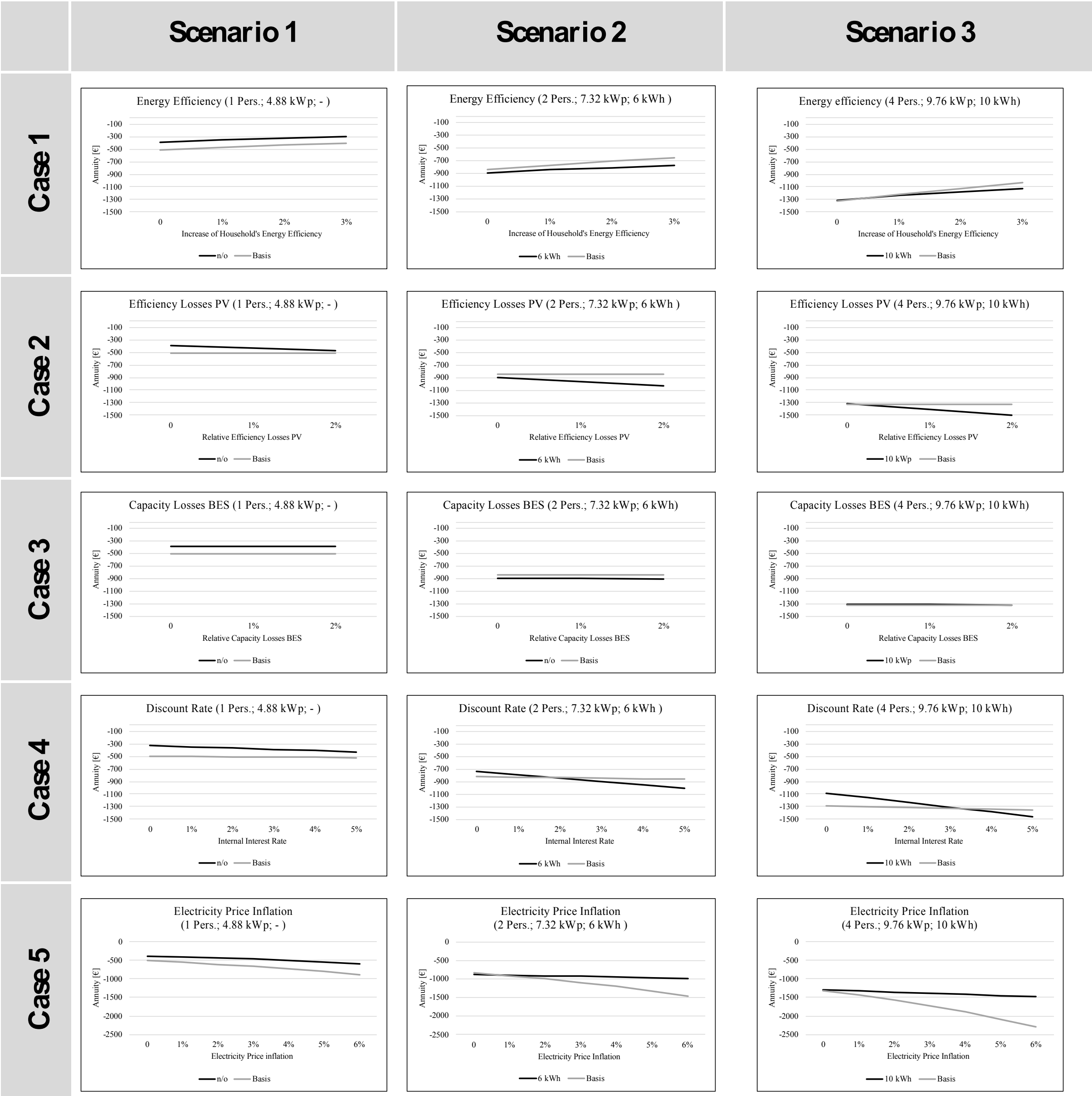

Figure 28: Results Sensitivity Analyses

2.4 Conclusions and Policy Implications

In this paper, we analysed investments in PV panels and BES systems under the current economic conditions and policy from a financial prosumer perspective. In particular, we focused on the situation in Germany with its specific market characteristics. The respective model of the prosumer allowed for investments in PV panels and BES systems in different capacity combinations. Our findings provide some clear guidelines for potential investors: Regardless of the size of the household, a PV system of any size will always create a positive financial added value compared to the "Basis" scenario (consumer model). Nevertheless, the larger the system, the more advantageous it is for the owner, whereas adding a battery storage system will not create a financial advantage in every scenario compared to the "Basis" scenario.

This outcome is different to the information that some suppliers provide to potential customers [83, 84]. For example, the calculations often include the full electricity price for self-consumption but neglect lost remunerations for fed-in electricity. This omission leads to too favourable economic results for additional storage capacity.

Such simplified calculations and the frequently observed non-economic factors can explain how investors are misled when they consider the economic consequences of their decisions. Shortcomings can also result from psychological and cognitive limitations [85, 86] and an often incomplete information base [87]. In order to compensate for these shortcomings, people use so-called heuristics when making their decisions. Bazermann and Moore (2009) [88] list a total of 21 heuristics used in decision making. A lot of these can be applied to the decision situation at hand with the consequence of a suboptimal economic decision. For example, biased decision makers can use confirmation heuristics [89, 90] to include selective data in their decisions that confirm their existing attitude. Loss aversion, which leads decision makers to perceive risks related to gains and losses differently, could also be relevant [91]. Together with varying future and present preferences, individual decision makers can thus come to very different assessments of investment opportunities, which cannot be purely explained by economic factors.

Even though the main focus of this paper is not the prosumer's self-sufficiency rate, it should be mentioned that the autarchy of the prosumer increases dramatically with the added BES. Furthermore, the self-sufficiency rate becomes higher with a larger battery capacity, but those increases are relatively small. The low correlation of financial efficiency and the self-sufficient rate is based, on the one hand, on the fact that a battery storage system only creates financial added value in the amount of the difference between the costs for electricity from the grid and the remuneration for fed-in electricity. On the other hand, the amount of self-generated electricity which is stored for one's own subsequent use is relatively small and can hardly be increased by larger battery sizes. Thus, the high purchase prices for batteries cannot be justified from the prosumer's point of view. This result points to possibly misallocated incentives for the prosumer model.

If there is a political will to increase the number of privately installed BES, then it is clear that the incentives need to be reconsidered. With an increasing share of RES, storage systems will be needed more and more to cover volatilities. Subsidies and remuneration systems for BES could be interlinked to the willingness of the owner to provide access to the storage system for stabilisation activities. With increasing numbers of smart charging options and a rising demand for electricity, local storage systems cannot only help to improve the self-sufficiency rate but also to help stabilise the grid.

In addition to the lack of a large-scale market structure for the prosumer model, some required equipment, such as a BES, is still expensive. In this paper, we investigated a wide range of possible scenarios which help to make the business model of a prosumer profitable and identified critical aspects that future market structures should consider if the investment by prosumers in BES systems is to become more attractive. The paper also shows that the required load for private prosumers is too small (depending on the size of the PV system). As already mentioned, political incentives could subsidize the installation of a BES system in a different way. Indeed, energy transition can proceed to the next step if an additional load, such as electric vehicles or combined heat pumps, is implemented into the system.

Another development which could increase the financial attractiveness of a BES is the use of so-called ancillary services. The storage capacities of numerous prosumers can be bundled by an aggregator who offers ancillary services for frequency and voltage control to system operators. As these services get remunerated, there is the opportunity of extra payment without additional or only low-cost investment. As services can potentially increase the efficiency of the energy system, it would be reasonable to create corresponding policy measures which support such a development.

As with every study, our work also has its limitations: Foremost, our work is based on data for the German market. As already mentioned, however, the applied model can easily be adapted to changes, since the basic problem structure remains the same. Future research can be carried out to investigate which changes and extensions can make investments in a BES profitable in the private sector. At this point we should mention the sector coupling with the aforementioned integration of electric vehicles or combined heating pumps. Furthermore, it should be evaluated to which extent a largely energy self-sufficient household can be a financial advantage. In addition, other, larger forms of private electricity generation such as biomass or small wind turbines could be considered. Integrating a financial evaluation of non-financial aspects such as autarchy could also be of interest. While our study covers solely financial aspects, an economic welfare effect is likely due to the intangible resource of self-sufficiency [92, 93] which is not represented by the considered cash-flows. Quantifying this welfare could explain why people already invest in BES despite our clear findings. In summary, the current incentives for prosumers promote investments in PV panels but not in electricity storage. If it is of political interest to increase the number of BES, then politicians still have to come up with appropriate solutions. A better interplay of locally generated electricity from different renewable sources would increase the proportion of renewably generated energy in households and would also promote the further decentralisation of the electricity market. In this vein, taking external costs and societal factors into account to develop a TCO model from a societal perspective could be an avenue worth researching in the future.

2.5 References for Research Paper 2

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2.6 Appendix of Research Paper 2

		Size of PV system (kW_p)									
		no PV	4.88			7.32			9.76		
		Annuity	Battery	Annuity	Self-sufficiency	Battery	Annuity	Self-sufficiency	Battery	Annuity	Self-sufficiency
Household size	1 Person 1714 kWh	-511.97	0	-387.24	47.37%	0	-302.07	49.58%	0	-219.71	50.83%
			6	-776.95	86.20%	6	-695.09	91.54%	6	-622.19	94.80%
			10	-992.72	87.36%	10	-909.5	92.61%	10	-836.6	95.83%
			16	-1258.86	88.16%	16	-1174.8	93.31%	16	-1102.14	96.53%
	2 Persons 2812 kWh	-839.94	0	-640.39	43.82%	0	-547.94	46.79%	0	-461.07	48.54%
			6	-988.44	75.86%	6	-887.97	82.84%	6	-802.93	86.85%
			10	-1200.98	77.35%	10	-1098.79	84.79%	10	-1011.34	88.96%
			16	-1465.53	77.84%	16	-1362.6	85.67%	16	-1274.04	90.28%
	3 Persons 3704 kWh	-1106.38	0	852.65	41.40%	0	-752.98	44.84%	0	-661.92	46.87%
			6	-1177.93	69.03%	6	-1062.26	76.69%	6	-968.14	81.18%
			10	-1387.15	70.63%	10	-1268.25	79.17%	10	-1169.87	84.08%
			16	-1649.99	71.45%	16	-1529.78	80.29%	16	-1430.33	85.43%
	4 Persons 4432 kWh	-1323.84	0	-1029.69	39.67%	0	-923.41	43.41%	0	-828.44	45.64%
			6	-1341.68	64.45%	6	-1215.03	72.41%	6	-1113.96	76.93%
			10	-1545.62	66.22%	10	-1415.1	75.08%	10	-1307.67	80.46%
			16	-1805.95	67.44%	16	-1674.87	76.24%	16	-1565.92	81.81%

Table 8: Results

Feed-in Tariff (€)	0.04	0.12	0.2	0.28	0.36	0.44	0.507
1 Pers.; 4.88 kWp; n/o	-675.04	-387.24	-99.44	188.36	476.17	736.97	1005
1 Pers.; 4.88 kWp; 6 kWh	-1005.8	-776.95	-548.1	-319.25	-90.4	138.45	330.11
1 Pers.; 4.88 kWp; 10 kWh	-1220.42	-992.72	-765.03	-537.33	-309.63	-81.94	108.76
1 Pers.; 4.88 kWp; 16 kWh	-1485.9	-1258.86	-1031.82	-804.78	-577.73	-350.69	-160.55
1 Pers.; basis	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97
2 Pers.; 7.32 kWp; -	-971.48	-547.94	-124.41	299.13	722.67	1146.2	1500.91
2 Pers.; 7.32 kWp; 6 kWh	-1220.87	-887.97	-555.08	-222.19	110.7	443.59	722.39
2 Pers.; 7.32 kWp; 10 kWh	-1428.23	-1098.79	-769.34	-439.9	-110.45	218.99	494.91
2 Pers.; 7.32 kWp; 16 kWh	-1690.43	-1362.6	-1034.78	-706.95	-379.12	-51.29	223.26
2 Pers.; basis	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94
4 Pers.; 9.78 kWp; -	-1370.72	-828.44	-286.17	256.1	798.37	1340.64	1794.79
4 Pers.; 9.78 kWp; 6 kWh	-1531.85	-1113.96	-696.06	-278.16	139.73	557.63	907.61
4 Pers.; 9.78 kWp; 10 kWh	-1714.17	-1307.67	-901.17	-494.68	-88.18	318.32	658.76
4 Pers.; 9.78 kWp; 16 kWh	-1968.25	-1565.92	-1163.59	-761.25	-358.92	43.42	380.37
4 Pers.; basis	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84

Table 9: Results Changed Selected Parameters – Feed-in Tariff

Battery Price	today's price	1 yr	2 yrs	3 yrs	4 yrs	5 yrs	6 yrs	7 yrs	8 yrs
	100%	90%	81%	73%	66%	59%	53%	48%	43%
1 Pers.; 4.88 kWp; n/o	-387.24	-387.24	-387.24	-387.24	-387.24	-387.24	-387.24	-387.24	-387.24
1 Pers.; 4.88 kWp; 6 kWh	-776.95	-728.89	-685.64	-646.7	-611.7	-580.19	-551.79	-526.29	-503.3
1 Pers.; 4.88 kWp; 10 kWh	-992.72	-922.82	-859.91	-803.28	-752.33	-706.51	-665.22	-628.09	-594.66
1 Pers.; 4.88 kWp; 16 kWh	-1258.86	-1162.2	-1075.2	-996.95	-926.44	-863.04	-805.97	-754.58	-708.38
1 Pers.; basis	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97	-511.97
2 Pers.; 7.32 kWp;	-547.94	-547.94	-547.94	-547.94	-547.94	-547.94	-547.94	-547.94	-547.94
2 Pers.; 7.32 kWp; 6 kWh	-887.97	-839.92	-796.67	-757.73	-722.72	-691.21	-662.81	-637.31	-614.32
2 Pers.; 7.32 kWp; 10 kWh	-1098.79	-1028.89	-965.97	-909.34	-858.39	-812.57	-771.29	-734.15	-700.73
2 Pers.; 7.32 kWp; 16 kWh	-1362.6	-1265.94	-1178.95	-1100.69	-1030.19	-966.79	-909.72	-858.33	-812.13
2 Pers.; basis	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94	-839.94
4 Pers.; 9.78 kWp; -	-828.44	-828.44	-828.44	-828.44	-828.44	-828.44	-828.44	-828.44	-828.44
4 Pers.; 9.78 kWp; 6 kWh	-1113.96	-1065.9	-1022.65	-983.71	-948.7	-917.19	-888.8	-863.29	-840.3
4 Pers.; 9.78 kWp; 10 kWh	-1307.67	-1237.77	-1174.87	-1118.25	-1067.3	-1021.45	-980.16	-943.02	-909.59
4 Pers.; 9.78 kWp; 16 kWh	-1565.92	-1469.26	-1382.26	-1304.01	-1233.5	-1170.1	-1113.03	-1061.65	-1015.44
4 Pers.; basis	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84	-1323.84

Table 10: Results Changed Selected Parameters – Battery Price

Energy Efficiency Improvement (per year)	0%	1%	2%	3%
1 Pers.; 4.88 kWp; n/o	-387.24	-356.17	-328.62	-304.15
1 Pers.; basis	-511.97	-470.72	-433.85	-400.86
2 Pers.; 7.32 kWp; 6 kWh	-887.97	-846.32	-810.31	-779.17
2 Pers.; basis	-839.94	-772.26	-711.77	-657.65
4 Pers.; 9.78 kWp; 10 kWh	-1307.67	-1239.7	-1180.89	-1129.97
4 Pers.; basis	-1323.84	-1217.16	-1121.83	-1036.52

Table 11: Results Sensitivity Analysis – Energy Efficiency Improvement

Efficiency Losses PV (per year)	0%	1%	2%
1 Pers.; 4.88 kWp; n/o	-387.24	-431.88	-472.04
1 Pers.; basis	-511.97	-511.97	-511.97
2 Pers.; 7.32 kWp; 6 kWh	-887.97	-959.13	-1024.07
2 Pers.; basis	-839.94	-839.94	-839.94
4 Pers.; 9.78 kWp; 10 kWh	-1307.67	-1405.49	-1494.85
4 Pers.; basis	-1323.84	-1323.84	-1323.84

Table 12: Results Sensitivity Analysis – Efficiency Losses PV

Capacity Losses BES (per year)	0%	1%	2%
1 Pers.; 4.88 kWp; n/o	-387.24	-387.24	-387.24
1 Pers.; basis	-511.97	-511.97	-511.97
2 Pers.; 7.32 kWp; 6 kWh	-887.97	-890	-893.05
2 Pers.; basis	-839.94	-839.94	-839.94
4 Pers.; 9.78 kWp; 10 kWh	-1307.67	-1310.1	-1313.38
4 Pers.; basis	-1323.84	-1323.84	-1323.84

Table 13: Results Sensitivity Analysis – Capacity Losses BES

Discount Rate	0%	1%	2%	3%	4%	5%
1 Pers.; 4.88 kWp; n/o	-328.84	-348.25	-367.75	-387.24	-406.67	-425.95
1 Pers.; basis	-497.06	-502.03	-507	-511.97	-516.94	-521.91
2 Pers.; 7.32 kWp; 6 kWh	-727.19	-780.63	-834.3	-887.97	-941.45	-994.54
2 Pers.; basis	-815.48	-823.36	-831.79	-839.94	-848.1	-856.25
4 Pers.; 9.78 kWp; 10 kWh	-1082.45	-1157.3	-1232.48	-1307.67	-1382.58	-1456.95
4 Pers.; basis	-1285.28	-1298.13	-1310.99	-1323.84	-1336.69	-1349.54

Table 14: Results Sensitivity Analysis – Discount Rate

Inflation Electricity Price	0%	1%	2%	3%	4%	5%	6%
1 Pers.; 4,88 kWp; n/o	-387,24	-411,47	-438,65	-469,16	-503,43	-541,89	-585,34
1 Pers.; basis	-511,97	-558,19	-610,02	-668,2	-733,58	-807,09	-889,81
2 Pers.; 7,32 kWp; 6 kWh	-887,97	-899,89	-913,25	-928,24	-945,08	-964	-985,28
2 Pers.; basis	-839,94	-915,77	-1000,8	-1096,26	-1203,51	-1324,12	-1459,83
4 Pers.; 9,78 kWp; 10 kWh	-1307,67	-1329,68	-1354,36	-1382,06	-1413,16	-1448,13	-1487,47
4 Pers.; basis	-1323,84	-1443,35	-1577,37	-1727,82	-1896,86	-2086,94	-2300,84

Table 15: Results Sensitivity Analysis – Inflation Electricity Price

3 Research Paper 3 – Financial and Environmental Potentials of Sector Coupling for Private Households

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Abstract

Promoting the German transition towards the generation of electricity from renewable sources, the federal government has created incentives to consumers for owning and operating private photovoltaic systems for residential buildings. Since the peak periods for generating electricity via photovoltaic systems and using electricity do not necessarily overlap, and guaranteed feed-in remunerations are likely to shrink or disappear in the future, households may increase their self-sufficiency by using storage systems. Nevertheless, various studies have shown that the use of battery energy storage does not yield sufficient financial benefits. Therefore, this study investigates the concept of sector coupling in order to understand the potential financial benefits of this new solution.

Implementing the Prosumer-Oriented Total Cost of Ownership approach, we analyse economic potentials of different variants of sector coupling for so-called prosumers under German market conditions. In these calculations we apply real-world data that cover weather, consumption patterns, operational and capital expenditures, energy prices, and possible revenues. This approach enables us to obtain realistic results and findings.

When applying different measures within the framework of sector coupling, we find that investments in battery energy storage systems do not pay off for prosumers under current German market conditions. Moreover, we show that carbon emissions from private households can be affected more by changing the energy-mix of supplied electricity than they can by increasing self-sufficiency.

Keywords

Energy Transition; Sector Coupling; Prosumer; Battery Storage

3.1 Introduction

For the energy transition in Germany, prosumers play an important role [1] by generating electricity over many decentralized sites. When producing electricity from renewable sources – in particular from photovoltaic (PV) systems – not only are prosumers important for future smart grids [2], they can also help to reduce carbon emissions by storing and consuming their self-generated energy [1, 3].

Hence, small-scale energy generation and storage is relevant not only from a technical but also from an economic perspective [4]. Locally stored electricity can be a valid option for buffering renewable energy in order to compensate gaps between local demand and local generation [4, 5]. In Germany, the installed PV capacity increased drastically from 0.114 GW in 2000 to 53.7 GW in 2020 [6–9]. Considering that PV is often used for local electricity generation by now, thus storage options have become more relevant. Even if the average subsidy for feed-in electricity per kWh is decreasing over time [6], some analysts see an increasing disposable income for prosumers [1].

In order to turn more consumers into prosumers, the concept of *prosumerism* needs to be financially attractive. In addition, a high level of autonomy and self-sufficiency can be a vital benefit of becoming a prosumer, as many consumers aspire to use a large part of their own electricity [1]. Kappner, Letmathe and Weidinger (2019) [10] emphasize that prosumerism can become financially profitable with changing market conditions, such as lower investment costs for batteries. This previous study shows that it is always financially advantageous to own and run a private PV system, but nevertheless that it is still not profitable to own battery energy storage (BES) systems under current market conditions. In 2018, there was no case where operating storage batteries in the home was financially beneficial [5].

The current paper investigates the profitability of several variations of the prosumer concept in combination with *sector coupling* in Germany. Sector coupling refers to the idea of interconnecting the sectors of electricity, heating, and transport. The concept includes the use of energy converters and storage solutions, allowing renewable electrical power to be used in order to reduce carbon emissions in the other sectors. Furthermore, transmission losses can be reduced and the throttling of power generation in peak times can be avoided by increasing the energy consumption through additional consumers [11].

The *prosumer* is defined as a consumer who also generates electricity for others [12]. For efficiency reasons, it is common to use storage systems and additional electrical load [13].

Often, prosumers are organized into private households and use small-scale PV- and/or battery systems [12, 14].

As one third of the energy demand is created by the household sector [15], sector coupling is an essential option for decreasing the demand for fossil energy sources. New technologies are arising that integrate demand for electricity, heat, and cooling [16]. One of the most discussed solutions is that of running heat pumps as energy buffers on the prosumer level [17]. In peak times, heat pumps can convert electricity into heat for later use as thermal energy. This technology is a promising addition to the prosumer concept for managing heating demand [18]. The concept of smart generation, i.e. algorithm-based demand management, and the use of electricity, heat, and cooling focuses on increasing the integration of renewable energy sources (RES) [19]. Increasing the electrical power level generated from renewable sources will lead to direct savings when using primary energy. With 100% electricity generated locally from RES, heat pumps will contribute substantially to reducing environmental impact [20]. In addition, heat pumps are more effective than traditional heating systems [21]. Rising numbers of heat pump sales show that these devices are accepted as an advanced alternative for generating heat [20]. The growing number of heat pumps in newly built houses confirms this assumption [22].

Coupling several energy sources and demands and decreasing investment costs for PV and BES can potentially promote rising independence of the prosumer [23]. Analyzing the prosumer from several perspectives shows that a PV-BES-based system is not financially beneficial compared to present solutions under current market conditions. However, self-sufficiency has more benefits than solely the monetary aspects. Increasing the consumption of the locally produced electricity can not only raise the level of self-sufficiency but can promote the economic feasibility of the prosumer model, as shown in this study. In Germany, adaptations in the system of government subsidies underline this approach [24].

This paper investigates a decentralized solution for sector coupling, with the option of generating and using electricity as the only energy source for each of the three domains, i.e. heating, electricity, and mobility. While our focus is on financial consequences, we consider additional aspects like self-sufficiency, local consumption, and carbon emissions too. The self-sufficiency rates of the scenarios highlight the importance of these parameters in the transition towards prosumerism.

As our analyses address the detailed household level using specific data, there is a clear distinction between this work and other studies in this area, which only refer to average quotas and which calculate average values that cannot be deployed realistically in a single facility.

3.2 Decentralized Supply of Domestic Households and Energy Autonomy

3.2.1 Previous Research

The concept of residential systems with PV and storage batteries has been well analysed and investigated in different papers. Chabaud et al. (2016) [25] present a new approach for energy management in residential microgrids. They evaluate their simulation against energy indicators as well as economic criteria. The center of their investigation is a household of two adults and two children living in a south-facing house.

Further studies develop and analyse models that focus on a combined PV-BES system [26–28]. Most of the scenarios also consider a part-time islanded mode for running the microgrids independently [26]. They use an optimization algorithm to calculate the feasibility and profitability of these systems [27]. In addition to examining management strategies, they investigate the impact of the capacity of the PV and battery system [28] on maximizing the consumption of locally generated energy.

Based on these research efforts, the prosumer model needs to be complemented by embedded market elements as well as possible operation and service layers [13]. Most of the studies prove that PV-BES systems for electrical self-sufficiency can partially create financial value [29] and can cover up to 70% of the needed electricity for residential buildings, depending on the building type [30]. This creates economic as well as social and environmental benefits [29].

Battery storage can significantly increase the energy autonomy [30]. Moreover, apart from the analysis of generating and storing electricity, previous research has investigated the increase in the share of own and self-generated energy by adding more consumption points. Toradmal et al. (2018) [17] introduced a heuristic optimization method for operating with different electricity-consuming assets such as a heat pump. They found that, even with a storage battery, not more than half of the demanded electricity can be covered by locally generated electricity using demand site management tools and switching off the heat pump in peak hours (from 4:00 p.m. to 7:00 p.m.). The research of De Coninck et al. (2014) [31] studies a microgrid of 33 single-family dwellings in Europe managing the demand of electricity and heat in combination with domestic hot water production. The study shows that PV inverter shutdowns can be strongly reduced by integrating electricity and heating.

The idea of sector coupling and local communities is also discussed in connection with other issues. As prosumers might be interested in trading energy, Haberl et al. (2013) [2] investigate the cheating problem in communities. Depending on the research perspective, it is not clear whether sector coupling leads to overall energy savings. Greening and Azapagic (2012) [32] performed a life cycle assessment of domestic heat pumps versus gas boilers, while Aye, Charters and Chaichana (2002) [33] compared conventional solar hot water systems with heat pumps. Arteconi, Hewitt and Polonara (2013) [18] focused on the optimization of the demand side for heat pumps. Depending on the respective assumptions, the considered authors discovered that smart forecast and demand management can maximize the rate of consuming locally generated energy [28]. Similarly to the findings of Kappner, Letmathe and Weidinger (2019) [10], Camilo et al. (2017) [4] showed that high battery prices are detrimental to the widespread use of PV-BES systems among prosumer households. Still, depending on government subsidies and retail prices of storage batteries, privately owned BES are likely to increase the self-sufficiency rate and profitability in the future [26].

Existing research proves the importance of investigating decentralized energy generation, storage, and demand control in order to create benefits for prosumers but also to turn the transition of the energy system into reality. This paper focuses on the additional demand caused by sector coupling to investigate the financial efficiency of prosumers. This is the first time that a study examines the financial perspective of a prosumer with additional loads due to sector coupling under German market conditions. While there is research on sector coupling, energy communities and prosumers, we have identified a lack of studies that combine these topics from the perspective of a prosumer.

3.2.2 Research Questions

According to sections 3.1 and 3.2.1, prosumers are essential agents in any energy transition. With a rising number of prosumers, it is important to understand the consequences they have to face in the future. As Kappner, Letmathe and Weidinger (2019) [10] have already shown, owning a battery is not financially profitable in the currently existing pricing and incentive structure in Germany. However, their study also shows that it is always advantageous to have a PV system. In this paper, we investigate whether a PV-BES-based prosumer model can pay off when considering additional load such as heating, hot water, and mobility demands. Hence, the paper addresses the following research question:

> **1st Research Question**
>
> Can the use of a battery energy storage (BES) system become financially advantageous for a private prosumer when considering all the energy needs of a domestic household?

In addition to this question, section 3.2.2 discussed how the prosumer model is aligned with the concept of sector coupling and can promote energy autonomy [34]. Decentralized energy generation and consumption should therefore also be aligned, especially when extending sector coupling in small-scale family homes. Since investment costs for autarchy-supporting assets, such as batteries or heat pumps, are still high, the second research question of this paper is as follows:

> **2nd Research Question**
>
> What improvements in self-sufficiency can be achieved if further energy demands in a domestic household are electrified?

3.3 Methodology

3.3.1 Analysis of Investment Alternatives

The aim of our work is to consider and to financially evaluate several investment opportunities concerning the energy supply of residential households. This should help to determine the most beneficial option for various technical configurations of the prosumer constellations.

There are two aspects to be considered here. First, there are the investment costs, i.e. capital expenditures, which should also include transaction costs. Second, operating expenditures and revenues are incurred during the utilization phase. The contribution margin is a helpful approach for evaluating and comparing the operational economic consequences of an investment. The revenues of a period and the costs attributable to the investment object allow us to determine whether one alternative has advantages over other solutions in a specific period [35]. For both types of expenditures (capital and operational), their values depend considerably on the available investment opportunities.

In addition, our considerations cover longer time periods, and there are financing effects that should not be neglected [36]. We assume that decision-makers need an overview of all financial consequences of the different investment opportunities and that the decision does not affect any financial streams other than our domain [37].

Respecting these facts, we use the total cost of ownership (TCO) concept [38] as the method of financial evaluation. The TCO concept takes a holistic view of investment objects, considering flows and activities even over longer periods [39]. The aim is to capture all costs (and revenues) associated with the investment object. This does not only include the capital and operational expenditures but also all transaction costs and end-of-life costs [38, 40]. Furthermore, there are aspects of service charges, administration, fees, maintenance, and so on, which are all considered in a comprehensive TCO [41, 42]. The key aspect examined in our research is the prosumer as a decision maker. Therefore, we apply a prosumer-oriented TCO.

The cash flows derived as described before must be processed into a single and sound result, which is a reasonable KPI to monitor decisions relevant for optimizing the relevant technical configurations. Based on the TCO concept, we first calculate the net present value based of the cash flows. Since the value calculated in this way covers the entire period under review and is difficult to classify in terms of scale, we then calculate the annuity, an annual amount that corresponds to the calculated net present value over the period under review. We deliberately do not relate the annuity to a functional unit (e.g. kWh) in order to preserve better comparability between alternatives. The calculation rules applied are presented below.

We calculate the net present value C_{NPV} by summing up all observed cash flows, which are discounted on an accrual basis, as shown in Equation 1.

$$C_{NPV} = C_{Capex} + \sum_{t=1}^{T} \frac{C_{Opex,t}}{(1+i)^t} \quad (1)$$

C_{Capex} is the capital expenditure, $C_{Opex,t}$ is the operational expenditure in period t, T is the total period under review, and i is the discount rate. The elements of C_{Capex} are all expenditures that occur in relation to purchasing the investment objects. $C_{Opex,t}$ stands for all operating cash flows accrued by running the system in period t.

As described above, we transfer the net present value into an annuity by using Equation 2.

$$C_{TCO_P} = C_{NPV} \frac{(1+i)^t * i}{(1+i)^t - 1} \quad (2)$$

C_{TCO_P} characterizes the annual prosumer-oriented total cost of ownership, also referred to as annuity in this study. C_{NPV} is the net present value calculated according to Equation 1, t is the index for the period during the period under review, and i is the discount rate.

3.3.2 Model

This section presents the structure of our model, and Figure 30 illustrates the main elements of the model. In line with the objectives of our work, the model covers the sectors of heating, electricity, and mobility. Based on the concept of sector coupling, these sectors are integrated with each other as shown in Figure 29. The starting point of the study is a domestic household, which is described by characteristics that determine the respective energy demand in the three sectors.

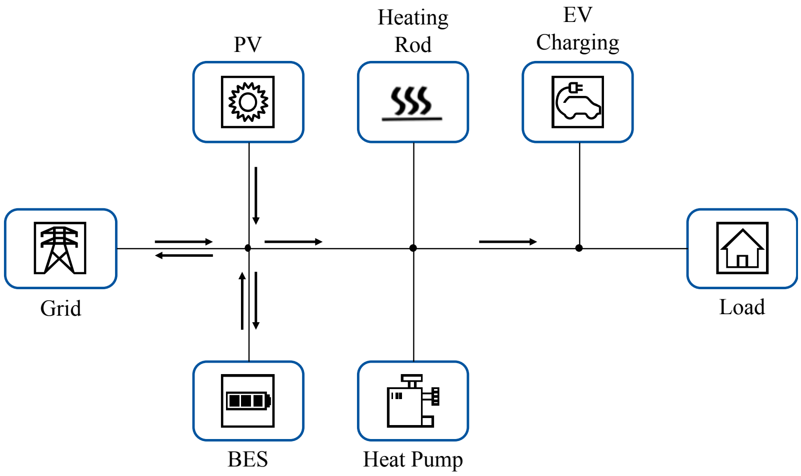


Figure 29: Prosumer Model with Sector Coupling

The annuity is central to our analysis; it is the annual financial burden over the entire observation period without considering investments in sector coupling and respective storage devices. The cash flow calculated for each period is used for this purpose. This annuity characterizes the basis for all subsequent analyses according to the following procedure:

First, there is the consumption of electrical energy through household appliances. This energy demand is directly included in the electricity balance. In addition, there is the self-generated electricity from a residential PV system. According to the findings from prior investigations [10], the size of the used PV system does not vary in this study, as the maximum allowable system (10 kW_p) is the most beneficial in financial terms. Nevertheless, the PV system is an investment object that is considered in the financial calculation. The use of BES is determined based on the resulting surplus or demand for electrical energy. The BES is an optional investment object available in various sizes. If there is a surplus of electrical energy, the battery is charged; if there is a deficit, it is preferable to draw power from the battery when possible. Since the purchase price for electrical energy is higher than the feed-in tariff, it is always the best financial strategy to make the most comprehensive use of the BES.

In the field of heating, there are two demands that need to be covered for any household: heating the living spaces and supplying hot water. One solution is to use a heat pump that meets both heating demands. The heat pump is powered by electricity. Alternatively, a conventional gas heating system can be used for heat supply. It is possible to supplement the gas heating with hot water preparation via a heating rod.

The mobility sector is considered by integrating a charging station for a battery electric vehicle (BEV) in the home. Irrespective of the size of the household, electricity requirements are determined for various mileages, which are included in the electricity balance. It is important to note that our model does not consider the investment in a BEV itself or the use of another car. In summary, the electricity balance jointly considers the variables 'household demand', 'generation of electricity by the PV system' and, optionally, the 'accumulative demand for heat pump, heating rod, and charging of an electric car'.

The interactions with the grid can be determined after calculating the respective quantities. If there is a surplus of electrical energy and the battery is fully charged, electricity is fed into the grid. In the opposite case of a deficit in connection with an empty battery, electricity is withdrawn from the grid. These two quantities of feeding-in and withdrawing electricity can be financially evaluated and are included in the operational cash flow (C_{OPEX}) calculated for each period. In addition, the optional purchase of gas for heating the home is added to the financial evaluation. Based on these mechanisms, various KPIs, such as NPV, annuity, or annual balances, are computed for the later evaluation of the scenarios examined.

Other KPIs, such as carbon emissions and the rate of self-sufficiency, are calculated on the basis of the electricity balance and the amount of electricity withdrawn and fed into the public distribution grid. The rate of self-consumption determines the share of self-generated electricity (from the PV system) that was also consumed by the household, after being stored in the BES. "Self-sufficiency" rate refers to the share of self-produced consumption against total consumption. This indicator is calculated for the levels of electricity but also in relation to overall energy. In other words, we calculate the self-sufficiency rate by considering electricity demand and generation but also including all energy streams, i.e. gas and electricity.

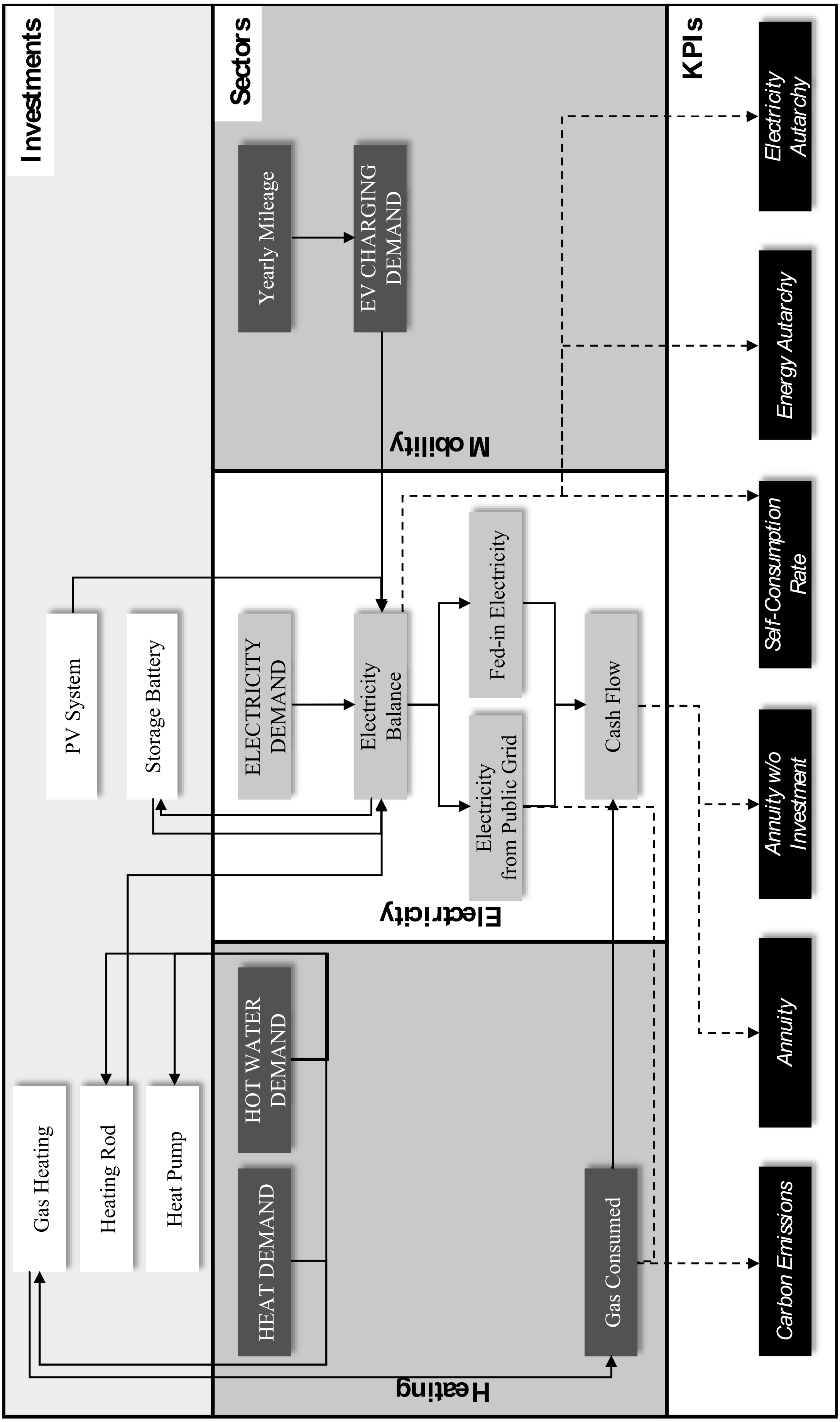


Figure 30: Model Structure

Finally, it is important to calculate the carbon equivalents associated with the purchases of electricity and gas. This allows to determine the carbon footprint and therefore the relevance of the different solutions for mitigating the GHG effect. For selected cases, which will be described in further detail below, the possible influence of carbon prices is determined.

3.3.3 Assumptions and Data Sources

One of the basic assumptions of the model is that the energy demand in each of the three sectors is always fully met. That is, restrictions for consumption due to supply deficits are not accepted.

According to several previous studies, we chose a time under review of 20 years [43–46]. This period is justified by various aspects. The period of 20 years is long enough to put the investment and use of the facilities in an appropriate relationship to each other. Furthermore, this period can be reliably surveyed to the extent that the technical performance of the facilities can be predicted over this period.

It is important to obtain comprehensible results to create added value from methodological and content-related points of view. For this purpose, it is best to determine all demand and production variables on a quarter-hour basis, i.e. for 15 min intervals. Other studies in our subject area just refer to averaged quotas and only calculate average values that cannot be achieved in reality in a single facility or residential home.

We estimate the amount of locally generated electricity on the basis of real values of global radiation [47] in Aachen, a major city in western Germany. Since global radiation has a proportional influence on the electricity generation of a PV system, we determine generation profiles that account for typical irregularities and imponderables that real weather conditions imply.

For the purposes of this study, we consider only a representative PV system with a nominal capacity of 9.76 kW_p at a price of € 11,399.68, including the inverter and installation [48]. The size of the PV system does not vary, as previous studies have shown [10] that this type of PV system should always be chosen without restriction to achieve the best financial outcome.

As described in the section above, the generation needs to match various electricity demands. They are calculated for household sizes of one to four persons, which we link to typical consumption values in Germany to identify different levels of power consumption.

For the original electricity consumption of a household, we use H0-consumption-profiles provided by a local distribution system operator (DSO) [49]. This again enables calculations based on real data.

In the heating sector, heating and hot water demands depend on the different sizes of the households. We consider three options for covering these demands:

1) Complete provisioning of the needed heat by a heat pump.

2) Complete utilization of gas heating.

3) Utilization of gas heating supplemented by hot water supply through a heating rod in the case of excess electricity.

For the heat pump, we select the configuration "air-water". Such a heat pump can achieve an annual coefficient of performance (COP) of 3. This means that 1 kWh of electricity can generate 3 kWh of heat. Here again, a consumption profile is provided by data from a network operator. Similarly to the procedure for a DSO, the demand profile is determined by the measured outside air temperature based on real weather conditions [50]. Using the temperature values associated with the global radiation, we determine the corresponding consumption values for the heat pump and include them in the calculations.

Furthermore, a similar profile for gas consumption is not necessary, because there is no interaction with other parts of the facility. The price of purchasing gas is quoted at 6 ct/kWh [51].

Table 16 provides an overview of all investment costs in this study [48, 52–54].

Asset	Price	
Battery Energy Storage	6 kWh	8,799 €
	10 kWh	12,799 €
	16 kWh	17,699 €
PV System	9.76 kW_p	11,399 €
Heat Pump		12,999 €
Gas Heating		5,990 €
Heating Rod		564 €

Table 16: Prices of Assets

For transportation, we have already illustrated how to determine the demand for electricity for residential charging of a BEV. Independent of the household size, we consider four annual mileages: 0 km, 10,000 km, 15,000 km, and 20,000 km [55].

Studies have shown that the average weekly mileage is divided up as follows: 18% per weekday (Monday to Friday) and 5% on Saturdays and Sundays. On weekdays the charging process starts at 6 p.m., on weekends at 3 p.m. [56]. The demand for electricity is based on the average consumption of 18.3 kWh/100 km [57]. It was also considered that the maximum charging current of the vehicle and the BES do not exceed given technical limits.

Based on the model described above, we combine the different flows to form an electricity balance. At this point, the BES is included in the balance with four options: 6 kWh, 10 kWh, and 16 kWh storage, or no BES at all. In line with using real data and achieving results that come as close as possible to the real user, we use models from a leading BES provider named "sonnen GmbH" for our calculations [52, 58].

As previous research has shown, storage batteries are still very expensive, and the high purchase prices for BES strongly influence the financial evaluation of the use of BES [10]. In order to study the effects of possible reductions in the purchase price, we investigate a reduction of investment costs in a scenario analysis.

In 2018, prosumers received 12 ct/kWh in remuneration for electrical energy fed into the public grid, based on the current edition of the "Erneuerbare-Energien-Gesetz" (EEG; Renewable Energy Law) [59]. The law already codifies slight reductions of this tariff over time. In another scenario analysis, this remuneration is varied downwards to examine the effects of possible future legal changes. The price for purchasing electricity is valued at 29 ct/kWh according to current average values [60].

For the carbon assessment, we determined the emission factors for electricity from the grid and for the gas burnt in the heating system. The average emission factor for electricity from the grid is 489 g/kWh [61]. In further computations, we reduced the share of carbon-based energy sources lignite, hard coal, oil, and gas from currently 48.32% [62] to 35% in 2030 according to national climate targets [63], which would result in an average emission factor of 354 g/kWh. For natural gas, we use an emission factor of 202 g/kWh carbon emissions [64].

3.4 Scenario Analysis

3.4.1 Basic Calculations

The methods and data described in chapter 3.3 help us to calculate the KPIs for all constellations considered. A central objective of our investigations is to calculate the economic efficiency of using BES while considering the opportunities of sector coupling for a private household. We are calculating three different energy supply variations with four types of household sizes and four battery sizes in each case. We picked the average household size of three persons to show selected results in Table 17. In general, the tendencies over all 192 calculated scenarios are similar and visible from the four examples in Table 17. Later on, we focus on heating scenarios, including heat pump and gas heating, since these are the scenarios in the fringe area. All values calculated are listed in Appendix of Research Paper 3. In the following we refer to single scenarios by using scenario numbers.

The first result is that the use of BES is not financially reasonable in any of the constellations considered. Irrespective of the size of the household, the type of heating, and the consideration of mobility, the absence of BES always leads to the lowest annuity, including the investment costs. For a larger and therefore more expensive BES, the annuity becomes worse. In the three-person household with heat pump and a 16 kWh BES, the annuity is € -3,485.81 (A12). The table only shows examples for 6 kWh BES to compare the least expensive BES scenario against the option without a BES.

Heating / Warm Water	House-hold [Pers.]	BES [kWh]	Annuity [€]	Annuity w/o Investment [€]	Self-Sufficiency Rate Electricity [%]	Self-Sufficiency Rate Energy [%]	Self-Consump-tion Rate [%]	CO_2 Equivalent [t]
Heat Pump	3	0	-2,769.44	-1,163.18	34.82	34.82	33.11	52.28
Heat Pump	3	6	-3,062.40	-903.95	52.88	52.88	50.29	37.79
Gas Heating	3	0	-2,346.27	-1,200.83	47.07	8.48	20.22	87.30
Gas Heating	3	6	-2,669.15	-971.52	82.46	14.85	35.42	74.48

Table 17: Selected Results

The results for the available options for heating living space and providing hot water are unequivocal. According to the calculations, heating with gas is always the least costly option. Again, no modification of the other parameters leads to a different outcome. The additional use of a heating rod does not create a financial benefit in any of the constellations considered.

Even though these results are not ambiguous, they can be analysed in more detail by looking into causes and interdependencies. When comparing the KPI “Annuity without Investment” with the KPI “Annuity with Investment”, it becomes clear that the high capital expenditures motivate the particular results. Excluding the capital expenditures from the calculations, the financial advantages of adding BES become apparent. In our example, there is an annual added value of about 300 € (with heat pump) or 230 € (with gas heating) of a 6 kWh BES in contrast to the scenarios without storage batteries. In that way, it is easy to identify any benefits of deploying BES. However, the savings are not sufficient to cover the investment costs over the planning horizon of 20 years. The achievable savings decrease with growing battery size, as Figure 31 shows for different household sizes in the heat pump scenario.

Furthermore, using a heat pump leads to increased savings of 369.16 € over the scenario with a 16 kWh battery compared to the scenario without battery, as the BES is used more extensively. However with gas heating, there are only savings of 252.99 € for the scenario with a 16 kWh battery compared to the scenario without battery. See Figure 32 below for this comparison.

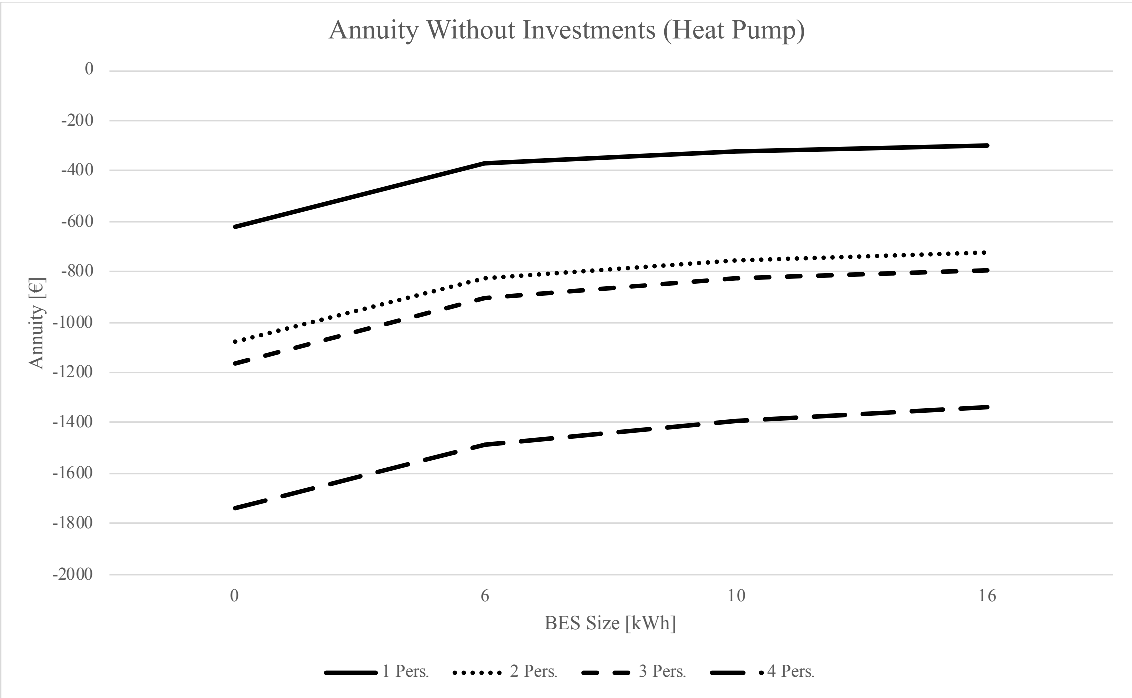


Figure 31: Annuity without Investments

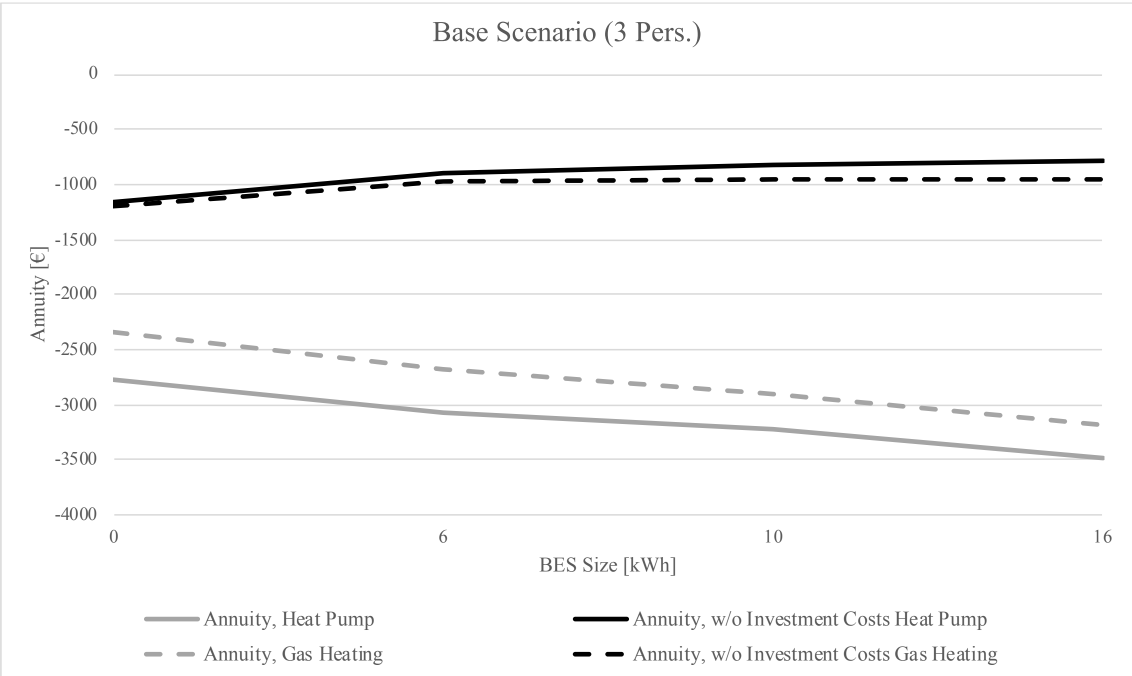


Figure 32: Base Scenario – Influence of Investment Costs

Omitting the investment costs, the annuity is quite similar when deploying gas heating and heat pumps. However, there are notable differences when looking at other KPIs. In both cases, the use of BES with 6 kWh can greatly increase self-sufficiency with regard to electricity. In the example with gas heating, this rate jumps from 47.07% to 82.46%, whereas using a heat pump helps to raise this rate from 34.82% to 52.88%. However, note that the calculation of self-sufficiency rate with gas heating does not reflect the heating of the homes. In the case of the heat pump, though, the supply of heat is included in this parameter because of the electricity consumption of the heat pump.

Therefore, the following analysis considers self-sufficiency including all energy generated and consumed, i.e. electricity and gas. The values of the scenario with heat pumps do not differ because there are no flows other than electricity. However, there are significant differences when heating homes with gas. Here, self-sufficiency rates are as low as 8.48% without BES and 14.85% with a 6 kWh BES. Consequently, using heat pumps helps to achieve the best possible self-sufficiency rate, and the highest share of local energy generation.

There are also clear differences for direct carbon emissions between the different scenarios. For this aspect, the examples chosen above are representative for this aspect too. In the example of the heat pump, there are 52.28 t of CO_2 equivalents without BES and 37.79 t with 6 kWh BES over the entire period under review. With gas heating, the values are dramatically higher: 87.30 t without BES and 74.48 t with a 6 kWh BES. Similarly, the rate of self-sufficiency improves notably with BES. The influence of potential carbon prices will be discussed in the sections 3.4.2 and 3.4.3.

In summary, the various KPIs in all scenarios improve when installing a BES system of 6 kWh as compared to no BES, except for the annuity. The improvement further rises when increasing the size of the BES (to 10 kWh and 16 kWh), but the rate of improvement decreases sharply.

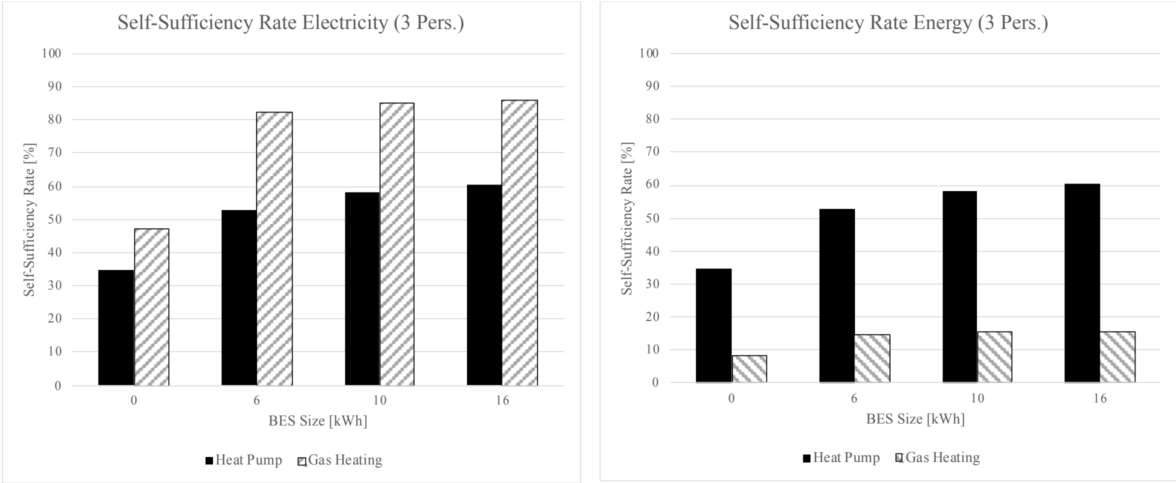


Figure 33: Self-Sufficiency Rate

This is justified by the course of self-sufficiency, shown for the scenarios A9-A12 and A25-A28 in Figure 33. Self-sufficiency is shown in relation to electricity (left) and total energy (right). The development described above can be seen: the introduction of the smallest BES size considered significantly increases self-sufficiency. Larger BES systems further increase self-sufficiency, but the rate of increase decreases. We distinguish between self-sufficiency related to electricity and that related to total energy. For the use of the heat pump, both quantities are the same. Thus, without BES, a 3-person-household achieves self-sufficiency of 34.82% (A9). With a 6 kWh BES, the value increases to 52.88% (A10), a 10 kWh BES (A11) and a 16 kWh BES (A12) lead to a self-sufficiency of 58.08% and 60.54% respectively. The course of the values for self-sufficiency with a gas heating system is similar. However, the absolute values compared to the heat pump are notable. While a high self-sufficiency is achieved with a gas heating system in terms of electricity (82.46% with 6 kWh BES; A26), the values for self-sufficiency in terms of overall energy are significantly lower (14.85% with 6 kWh BES; A26). This shows the strengths of the electricity/heating sector coupling with the heat pump.

For scenarios using heating rods, none of the constellations show financial advantages. As the heating rod is only activated in the case of excess electricity, it often consumes electricity that is valued at 12 ct/kWh if it was fed into the grid, or with 17 ct/kWh if it was stored in the BES instead. In our calculations, electricity stored in BES saves 17 ct/kWh, as it does not need to be withdrawn from the public grid for 29 ct/kWh when being consumed, while it cannot be fed into the grid for 12 ct/kWh. Both values (12 ct/kWh and 17 ct/kWh) exceed the price of gas for water heating instead so there is no opportunity for savings via the use of a heating rod. There are increases in the rates of local energy consumption, self-sufficiency, and carbon equivalents against heating with gas, but these are minor in all constellations, as the results in Appendix for Research Paper 3 show (e.g. A22 compared to A38).

For the analysis for the sector of mobility, the findings when integrating BEV loading at home can be quickly described. The evaluations cover the same KPIs as for the other sectors above. Charging electric vehicles at home has considerable impacts on the results of the different constellations. However, we could not identify any case where adding BES changes any relations of the KPIs. This is not surprising, as vehicle charging is a linear process mostly depending on the mileage driven. Thus, there are impacts on the amount of electricity consumed, but there are no changes in the proportionalities of the results.

3.4.2 Assessment of Sector Coupling Investigations

When studying PV-heat-pump systems in residential homes, other authors have found that self-generated electricity can barely increase the financial benefit of using a heat pump [20]. In this vein, this paper confirms these results but also shows that using a battery storage for intermediate energy storage can substantially increase the self-sufficiency rate of private households.

As our results in section 3.4.1 and the results of [32] show, heat pumps have a positive environmental impact compared to gas boilers. Thus, the deployment of heat pumps should be promoted to increase ecological sustainability of heating water. As PV-generated electricity is more readily available in summer, while heating demand peaks in Europe during the winter months, using battery storage can improve the performance of a residential micro-grid. Moreover, a heat pump can be a supportive tool for a local demand management system [18] in terms of compensating energy peaks.

Our calculations include three different scenarios for generating energy. First, we considered a PV-BES system with a heat pump in a fully electricity-based scenario. Second, we considered a PV-BES system with gas heating for water and heat demand. This scenario reflects the alternative with the lowest electricity consumption. In a third scenario, we added a heating rod to the gas heating to create an intermediate scenario between the two opposites. Our calculations led to four distinct findings which are described below.

Investment costs are a crucial factor

First, investment costs for BES negatively impact decisions for their deployment. In addition, the investment costs of a heat pump are higher than those of a comparable gas heating system. From a monetary point of view, a PV-BES system with gas heating is financially more beneficial than a PV-BES system combined with a heat pump. Considering the carbon emissions, this result is harmful from an environmental perspective, as Table 4 1 shows.

Moving on, our research confirms the results of former studies [10] that the investment costs of storage batteries are too high if they have to be paid for from the savings from using self-generated energy. This result also holds when adding more demand to residential microgrids. Even with the maximum demand calculated, in a four-person household with a heating pump and the small battery size of just 6 kWh (A14), the annuity is 300.60 € lower compared to not investing in a BES system (A13).

The financial disadvantages of high investment costs could be compensated by potential CO_2 pricing. Figure 34 shows the corresponding annuities of scenarios A9 and A10 assuming a pricing of CO_2 emissions.

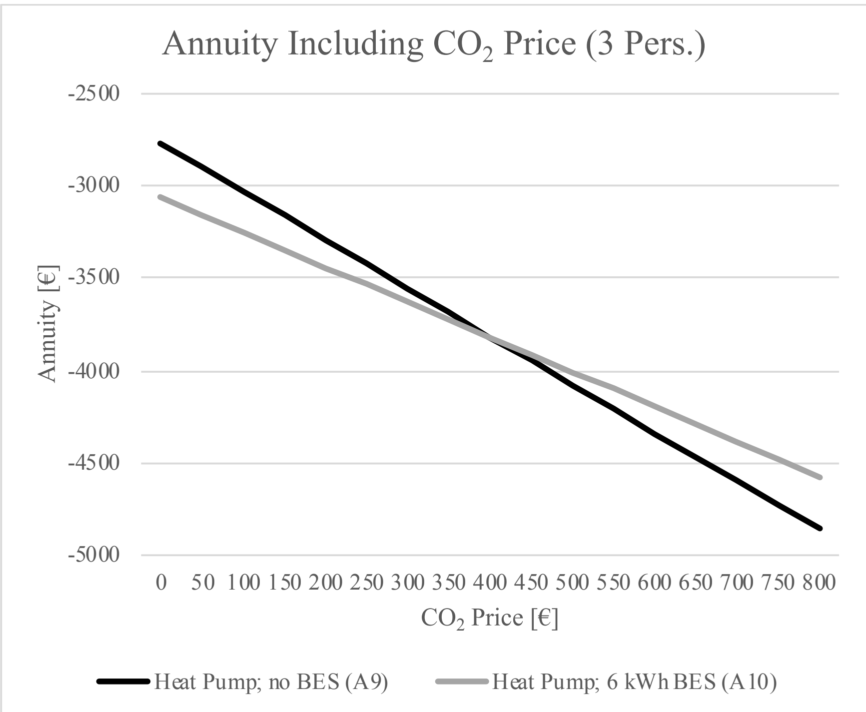


Figure 34: Annuity Including CO_2 Price (3 Pers.) I

Due to the CO_2 emissions reduced by the BES the financial disadvantage of the scenario with BES is compensated with an increasing CO_2 price. A virtual price of 406.88 €/t leads to balanced annuities. This price might be quite unrealistic today, but it shows that CO_2 pricing is one measure to increase the financial advantageousness of a BES system together with other changes in framework conditions.

Ignoring investment costs affect the results

This outcome is only different if the investment costs are ignored in general i.e. if the operation costs alone are considered. Only then will the costs of energy decrease due to the higher shares of locally generated and consumed energy. Moreover, larger storage batteries lead to better annuities, as prosumers can consume higher amounts of locally produced electricity. These effects apply to all scenarios, but the impact is higher for prosumers with larger electricity demand. The financial results can be explained by the rate of self-sufficiency, which increases in a four-person household with a heat pump from 32.40% without BES to 46.18% with a 6 kWh BES.

Variation of the battery size has higher impacts in the heat pump-scenario than in the gas heating scenario

Since the heat pump scenario is fully based on electricity, increasing the battery size affects the results of the heat pump scenarios more than those of scenarios with full or partial gas heating. This applies to every key parameter. For instance, the self-sufficiency rate in a three-person scenario with a heat pump increases from 52.88% with a 6 kWh BES to 60.54% with a 16 kWh BES, while it only increases from 14.85% with 6 kWh BES to 15.52% with a 16 kWh BES with the same settings but with gas heating instead of a heat pump.

Prices for natural gas are too low to make heat pumps competitive

Considering the energy carrier, note that a heat pump system emits less CO_2 than a gas heating system does, based on our calculations. However, the investment costs for a gas heater are significantly lower. This results from two factors. First, the technical equipment is much more common and advanced, and this helps to lower the investment costs for gas heaters. Second, the prices for purchasing natural gas are quite low. In Germany, one kWh of natural gas costs 6-7 ct on average [51]. Moreover, the taxation of gas is very different from that of electricity. While the average level of taxes and levies on electricity are approx. 80% on the net price, gas only has a rate of taxes and levy of 20% [60]. A general carbon emission tax could possibly correct these effects, as the results of our emission assessments show. Figure 35 shows the influence of the CO_2 price on the annuities of scenarios A9 and A25. The analysis reveals that the financial benefits of the gas heater compared to the heating pump are compensated at a CO_2 price of 241.81 €/t, which takes into account the higher emissions of a gas heater. Again, this price might be slightly unrealistic at the moment but it does show the potential effect.

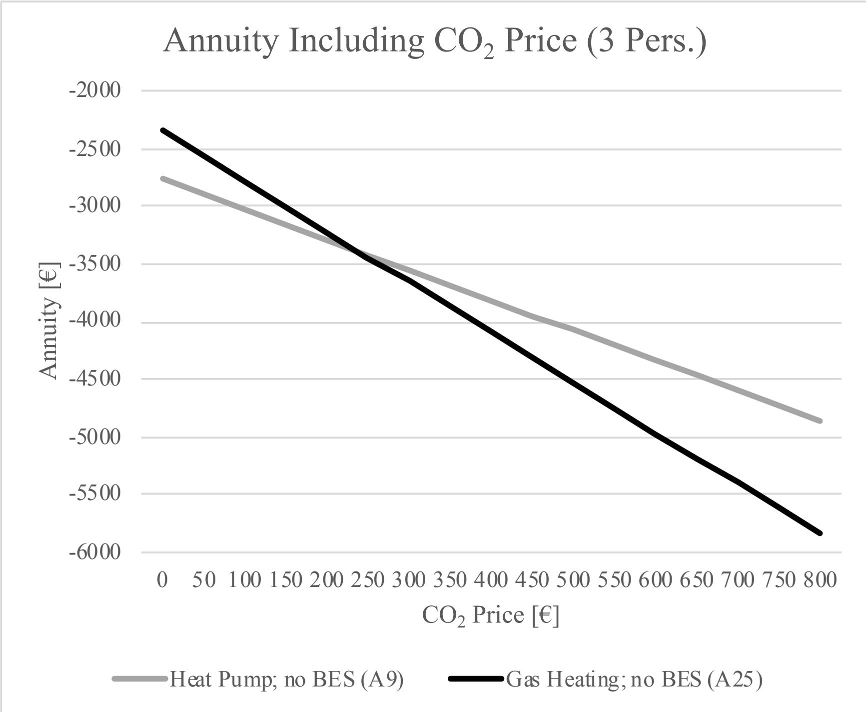


Figure 35: Annuity Including CO_2 Price (3 Pers.) II

3.4.3 Sensitivity Analysis

The calculations above have all been based on fixed boundary conditions. These conditions reflect the current status of the incentive system as well as the market conditions in Germany. For the future, it is reasonable to assume that these boundaries and market conditions will change. We consider four realistic changes for the future in the following scenario variations. The changes are the additional electricity needed to charge a BEV in the home, the changes when battery prices drop to half of their current value, changes in the external energy mix and the reduction of the subsidies for feeding electricity into the public grid.

Sensitivity Analysis with EV, ceteris paribus

In this case we exclusively add additional demand for electricity. The extra demand is created by an existing EV with average technical boundary conditions and average daily use. Therefore, the electricity consumption is growing linearly, assuming additional consumption for mileages of 0 km, 10,000 km, 15,000 km, and 20,000 km per year. Moreover, the financial advantageousness of using BES ascertainable due to adding an EV remains unchanged for all scenarios. However, the self-sufficiency rate decreases and the rate of local energy consumption increases. For example, on the basis of scenario A10, the self-sufficiency rate decreases from 52.88% to 45.11% by adding an EV with a yearly mileage of 10,000 km (B10), whereas the self-consumption rate slightly increases from 50.29% to 52.48%. Generally, it can be said that every 10,000 km per year raises the energy costs by about 500 € per year, according to our findings.

Sensitivity Analysis with lower battery investment costs, ceteris paribus

We also vary the investment costs for the installed batteries in several cases. Since the battery prices have been falling in recent years, it makes sense to consider lower battery prices when examining possible future scenarios. In this scenario, we consider batteries as one large investment at the beginning of the period under review. Thus, we halve the battery prices to show the effects of future improvements in mass-producing storage batteries with high performance.

In this case, the annuities are becoming similar between the no-battery scenario and the PV-BES-analysis, as Figure 37 (Panel A & B) shows. The two major findings of this analysis are: 1) Even if the battery prices are halved, the annuities with or without a BES system are not clearly advantageous for either of the two cases. 2) The gas heat is still financially advantageous in comparison to the heat pump.

Nevertheless, regarding 1) we can show that assuming halved BES prices and a relatively low CO_2 price of 40.71 €/t would lead to financial superiority of BES (see Figure 36). This result illustrates that a combination of changes in framework conditions is needed to support the financial attractiveness of BES.

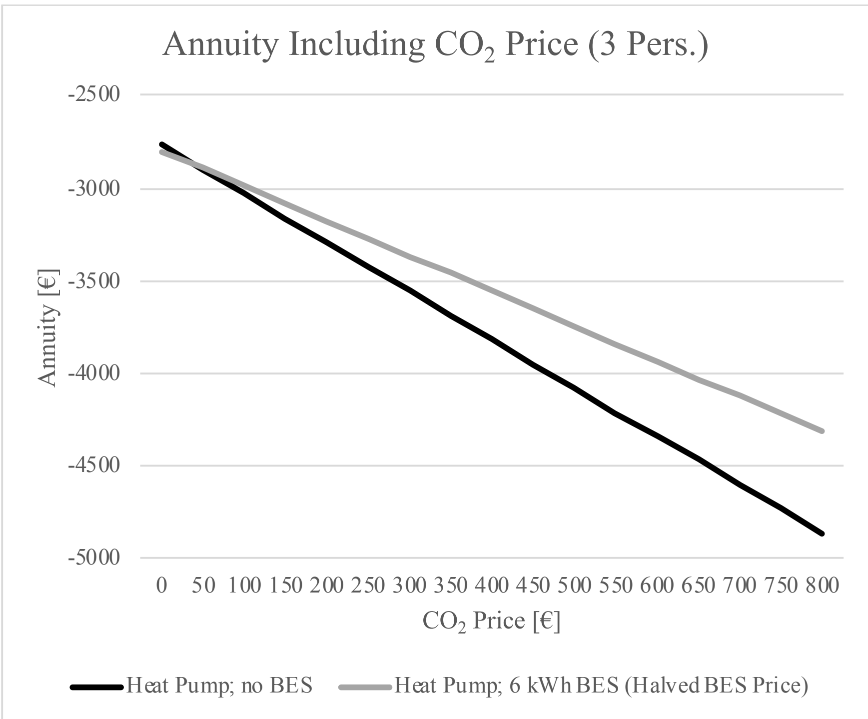


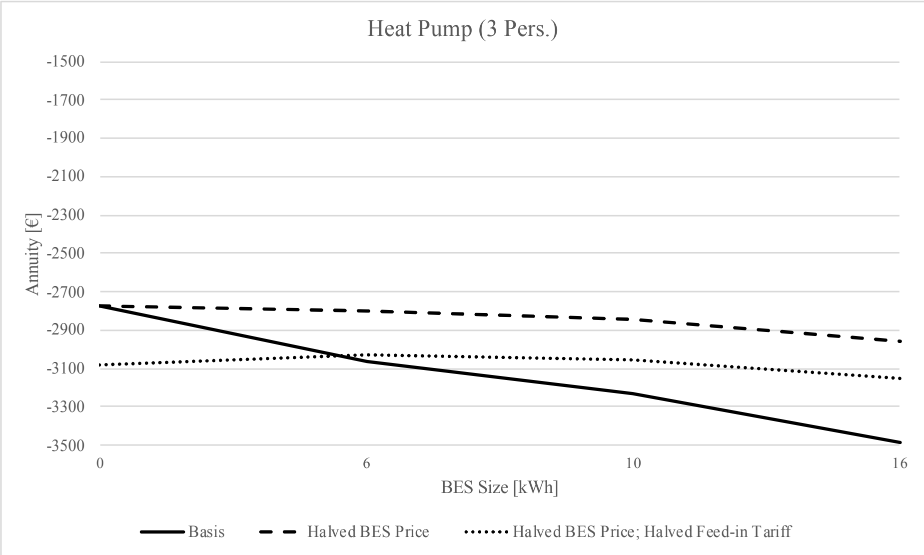
Figure 36: Annuity Including CO_2 Price (3 Pers.) III

Sensitivity Analysis with lower battery investment cost plus lower feed-in tariffs, ceteris paribus

Besides lower battery prices, we also consider a decreased feed-in tariff for electricity from 12 ct/kWh to 6.8 ct/kWh. In consequence, the annuities of every sensitivity analysis are increasing, which can be explained by lower revenues for the electricity fed into the public grid. In this case, however, using small batteries becomes financially more profitable compared to the no-battery analysis in every variation when both owning a heat pump, see Figure 37 panel A, and owning a gas heating system, see Figure 37 panel B. This can be explained by a larger difference between the prices for consuming and feeding in electricity to the public grid. The margin for self-generated and consumed electricity is valued at a higher level in this case. Furthermore, the results show that profitability with lower feed-in tariffs rises with higher consumption. In addition, the financial advantage grows with the size of the storage battery.

In summary, the findings demonstrate that fixed feed-in subsidies promote the deployment of local PV systems in residential areas. But the use of small-scale local BES will only be profitable if both the investment price for batteries falls and the fixed feed-in tariffs drop.

Panel A



Panel B

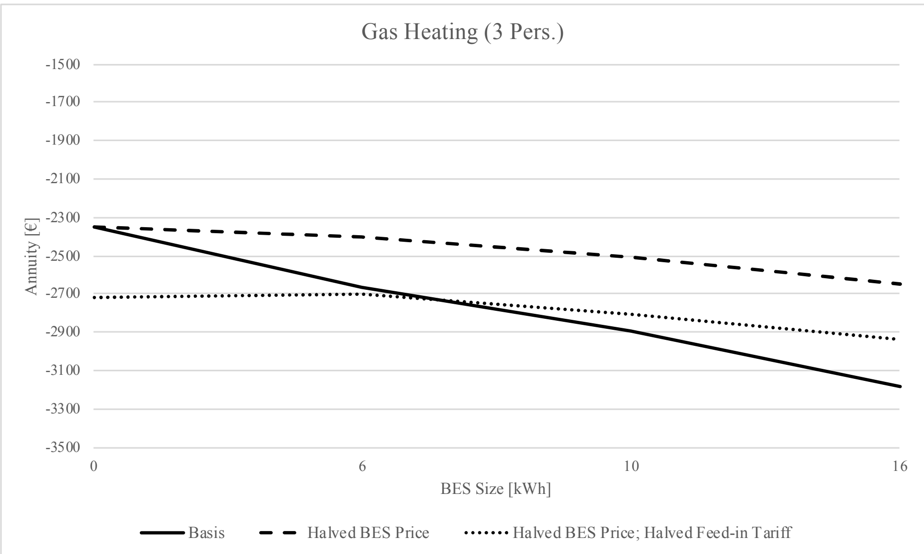


Figure 37: Sensitivity Analysis – Heat Pump and Gas Heating

Sensitivity Analysis with 35% fossil energy in the electricity mix, ceteris paribus

Apart from small-scale projects supporting the transition of the energy system in Germany, the German government supports the energy transition in large-scale projects as well. The German roadmap intends to decrease the share of electricity generated from fossil sources to 35% by 2030. This change will affect the carbon emissions for all processes using electricity.

In our sensitivity analyses, this change leads to a decrease in carbon emissions in all variations when consuming "greener electricity" from the public grid. Overall, the expected changes in the energy mix lead to a decrease in the carbon emissions from 37.8 t to 30.2 t for a three-person household with heat pump and without BEV. Such changes in the energy mix have a higher impact on the overall carbon emissions than any increase in the level of locally generated energy through using a larger BES (a minimum of 31.6 t) does. The same results are found in cases with lower or higher energy consumption or with different heating options.

In summary, the results show that changing the electricity mix in the grid has a larger effect on the overall carbon emissions than providing storage batteries for decentralized generated electricity does, even when decentralized generated electricity is 100% renewable.

3.5 Conclusion and Policy Implications

Even when applying the concept of sector coupling, the use of a BES system does not become economically beneficial under the current conditions of the German market. Furthermore, linking the electricity sector with the heating sector by using a heat pump or a heating rod leads to financial disadvantages for the prosumer, even when additional load can help to promote the amortization of BES.

This study has shown the reasons for these findings. Based on real data, we found that the desired effects of increasing the levels of self-sufficiency and locally consumed energy can be achieved. Nevertheless, the financial gains stemming from the use of a BES system or heat pumps are not sufficient to pay for the high initial costs, even under a long period under review. However, we have also illustrated how future developments may make the use of BES beneficial to prosumers from a financial point of view. The effects of decreased BES prices are obvious, but a reduction in feed-in tariffs could also drastically change the economic situation. Such changes in the prerequisites will increase the margins of using BES. Thus, reducing government subsidies for fed-in electricity can increase the use of BES in residential microgrids and can therefore contribute to the energy transition. Furthermore, we have investigated the potential effects of CO_2 pricing. Although solely introducing a CO_2 price will hardly lead to the financial advantageousness of a BES system or a heat pump compared to gas heating, in combination with other measures and changes in the framework conditions, the economically preferrable alternatives can change with a CO_2 price.

As these results focus on the individual budget and primarily the financial consequences, other aspects need to be considered in further considerations too. The non-financial arguments could be more relevant for the individual prosumer as a decision-maker. An increase in self-sufficiency and a growing use of self-generated electricity from renewable sources can be essential values that are well appreciated in an investment decision.

Furthermore, the relevant authorities need to decide which energy use by private households is considered desirable and worthy of support. The advantage of this study is the use of real data instead of theoretical considerations, which constitutes a major improvement over previous research. Our work contributes in this respect by showing the effects which can be achieved by changes in government subsidies and which sustainable options could be promoted with additional financial support.

Even though the research paper gives a comprehensive overview of the financial benefits for private prosumers who are involved in sector coupling and provides an outlook of the impact on CO_2 emission levels, some limitations are relevant. One limitation is not considering smart solutions in the calculations. Smart solutions can help to manage energy demands by smoothening peak demands or, in times of peak electricity generation, rescheduling additional demand in order to maximize self-sufficiency rates.

Further research should consider energy communities. So-called energy communities support the idea of single prosumers supporting each other by distributing electricity within the energy community. The cumulated energy demand of these households smoothens itself by lowering the peaks, due to the different timing of high-demand time intervals of individual consumers. Moreover, a comprehensive life cycle assessment can help to better estimate the environmental impact of prosumers by additionally considering impacts from both production and the end-of-life phase of assets as well as further emission categories.

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3.7 Appendix of Research Paper 3

	Annual Mileage BEV:		0 km							
Scenario #	Heating	Warm Water	Household [Pers.]	BES [kWh]	Annuity [€]	Annuity w/o Investment [€]	Self-Sufficiency Rate Electricity [%]	Self-Sufficiency Rate Energy [%]	Self-Consump-tion Rate [%]	CO_2 Equivalent [t]
A1	Heat Pump	Heat Pump	1	0	- 2,224.94	- 618.67	35.30	35.30	24.28	37.54
A2	Heat Pump	Heat Pump	1	6	- 2,529.73	- 371.28	59.14	59.14	40.68	23.70
A3	Heat Pump	Heat Pump	1	10	- 2,718.17	- 320.01	64.08	64.08	44.08	20.84
A4	Heat Pump	Heat Pump	1	16	- 2,991.82	- 300.03	66.01	66.01	45.41	19.72
A5	Heat Pump	Heat Pump	2	0	- 2,685.04	- 1,078.78	34.12	34.12	30.88	50.30
A6	Heat Pump	Heat Pump	2	6	- 2,982.20	- 823.74	52.79	52.79	47.79	36.04
A7	Heat Pump	Heat Pump	2	10	- 3,151.28	- 753.13	57.96	57.96	52.46	32.09
A8	Heat Pump	Heat Pump	2	16	- 3,412.62	- 720.83	60.32	60.32	54.60	30.29
A9	Heat Pump	Heat Pump	3	0	- 2,769.44	- 1,163.18	34.82	34.82	33.11	52.28
A10	Heat Pump	Heat Pump	3	6	- 3,062.40	- 903.95	52.88	52.88	50.29	37.79
A11	Heat Pump	Heat Pump	3	10	- 3,227.51	- 829.36	58.08	58.08	55.24	33.62
A12	Heat Pump	Heat Pump	3	16	- 3,485.81	- 794.02	60.54	60.54	57.58	31.65
A13	Heat Pump	Heat Pump	4	0	- 3,343.21	- 1,736.95	32.40	32.40	39.18	68.95
A14	Heat Pump	Heat Pump	4	6	- 3,643.90	- 1,485.44	46.18	46.18	55.84	54.89
A15	Heat Pump	Heat Pump	4	10	- 3,794.23	- 1,396.07	51.07	51.07	61.77	49.90
A16	Heat Pump	Heat Pump	4	16	- 4,032.57	- 1,340.78	54.10	54.10	65.42	46.81
A17	Gas Heating	Gas Heating	1	0	- 1,839.42	- 693.98	50.99	4.99	10.14	72.12
A18	Gas Heating	Gas Heating	1	6	- 2,258.24	- 560.61	95.68	9.35	19.02	64.65
A19	Gas Heating	Gas Heating	1	10	- 2,494.03	- 556.70	97.27	9.51	19.33	64.41
A20	Gas Heating	Gas Heating	1	16	- 2,785.67	- 554.70	98.21	9.60	19.52	64.28
A21	Gas Heating	Gas Heating	2	0	- 2,260.54	- 1,115.10	48.67	6.35	15.87	89.77

A22	Gas Heating	Gas Heating	2	6	- 2,618.37	- 920.74	88.23	11.52	28.77	78.90
A23	Gas Heating	Gas Heating	2	10	- 2,848.23	- 910.90	90.33	11.79	29.46	78.34
A24	Gas Heating	Gas Heating	2	16	- 3,137.09	- 906.12	91.38	11.93	29.80	78.06
A25	Gas Heating	Gas Heating	3	0	- 2,346.27	- 1,200.83	47.07	8.48	20.22	87.30
A26	Gas Heating	Gas Heating	3	6	- 2,669.15	- 971.52	82.46	14.85	35.42	74.48
A27	Gas Heating	Gas Heating	3	10	- 2,892.17	- 954.84	85.06	15.32	36.54	73.55
A28	Gas Heating	Gas Heating	3	16	- 3,178.81	- 947.84	86.14	15.51	37.00	73.16
A29	Gas Heating	Gas Heating	4	0	- 2,860.20	- 1,714.76	45.90	7.56	23.59	114.29
A30	Gas Heating	Gas Heating	4	6	- 3,162.87	- 1,465.23	78.08	12.86	40.13	100.34
A31	Gas Heating	Gas Heating	4	10	- 3,377.47	- 1,440.14	81.31	13.39	41.79	98.94
A32	Gas Heating	Gas Heating	4	16	- 3,661.84	- 1,430.87	82.50	13.58	42.41	98.42
A33	Gas Heating	Heating Rod	1	0	- 1,902.04	- 719.47	62.90	8.19	16.51	69.34
A34	Gas Heating	Heating Rod	1	6	- 2,324.32	- 589.56	95.85	12.48	25.17	62.06
A35	Gas Heating	Heating Rod	1	10	- 2,559.48	- 585.01	97.16	12.65	25.51	61.79
A36	Gas Heating	Heating Rod	1	16	- 2,850.41	- 582.32	98.02	12.76	25.74	61.63
A37	Gas Heating	Heating Rod	2	0	- 2,325.35	- 1,142.78	57.67	9.19	22.80	86.75
A38	Gas Heating	Heating Rod	2	6	- 2,690.61	- 955.85	89.03	14.19	35.20	76.30
A39	Gas Heating	Heating Rod	2	10	- 2,920.95	- 946.48	90.65	14.45	35.84	75.77
A40	Gas Heating	Heating Rod	2	16	- 3,209.76	- 941.66	91.49	14.58	36.17	75.50
A41	Gas Heating	Heating Rod	3	0	- 2,407.15	- 1,224.57	53.50	11.04	26.16	84.71
A42	Gas Heating	Heating Rod	3	6	- 2,737.90	- 1,003.14	83.53	17.23	40.84	72.33
A43	Gas Heating	Heating Rod	3	10	- 2,961.98	- 987.51	85.65	17.67	41.88	71.46
A44	Gas Heating	Heating Rod	3	16	- 3,249.08	- 980.98	86.53	17.85	42.31	71.10
A45	Gas Heating	Heating Rod	4	0	- 2,927.18	- 1,744.60	52.77	10.01	31.06	111.03
A46	Gas Heating	Heating Rod	4	6	- 3,240.60	- 1,505.84	79.65	15.11	46.89	97.69
A47	Gas Heating	Heating Rod	4	10	- 3,458.16	- 1,483.69	82.14	15.58	48.35	96.45
A48	Gas Heating	Heating Rod	4	16	- 3,742.75	- 1,474.65	83.15	15.78	48.95	95.95

Table 18: Result Table I

	Annual Mileage BEV:		10,000 km							
Scenario #	Heating	Warm Water	Household [Pers.]	BES [kWh]	Annuity [€]	Annuity w/o Investment [€]	Self-Sufficiency Rate Electricity [%]	Self-Sufficiency Rate Energy [%]	Self-Consump-tion Rate [%]	CO_2 Equivalent [t]
B1	Heat Pump	Heat Pump	1	0	- 2,745.13	- 1,138.86	28.92	28.92	26.03	53.96
B2	Heat Pump	Heat Pump	1	6	- 3,013.63	- 855.18	49.81	49.81	44.83	38.10
B3	Heat Pump	Heat Pump	1	10	- 3,140.37	- 742.22	58.12	58.12	52.32	31.79
B4	Heat Pump	Heat Pump	1	16	- 3,374.19	- 682.40	62.52	62.52	56.28	28.45
B5	Heat Pump	Heat Pump	2	0	- 3,209.06	- 1,602.79	28.97	28.97	32.37	66.93
B6	Heat Pump	Heat Pump	2	6	- 3,488.42	- 1,329.97	45.15	45.15	50.45	51.68
B7	Heat Pump	Heat Pump	2	10	- 3,606.31	- 1,208.15	52.38	52.38	58.53	44.87
B8	Heat Pump	Heat Pump	2	16	- 3,820.08	- 1,128.29	57.11	57.11	63.82	40.41
B9	Heat Pump	Heat Pump	3	0	- 3,294.92	- 1,688.65	29.66	29.66	34.51	69.00
B10	Heat Pump	Heat Pump	3	6	- 3,575.96	- 1,417.50	45.11	45.11	52.48	53.84
B11	Heat Pump	Heat Pump	3	10	- 3,692.26	- 1,294.11	52.14	52.14	60.65	46.95
B12	Heat Pump	Heat Pump	3	16	- 3,899.55	- 1,207.75	57.06	57.06	66.37	42.12
B13	Heat Pump	Heat Pump	4	0	- 3,871.47	- 2,265.21	28.41	28.41	40.38	85.82
B14	Heat Pump	Heat Pump	4	6	- 4,168.03	- 2,009.58	40.33	40.33	57.32	71.53
B15	Heat Pump	Heat Pump	4	10	- 4,286.19	- 1,888.04	45.99	45.99	65.38	64.74
B16	Heat Pump	Heat Pump	4	16	- 4,474.75	- 1,782.96	50.89	50.89	72.34	58.87
B17	Gas Heating	Gas Heating	1	0	- 2,352.12	- 1,206.67	30.11	5.51	12.38	88.12
B18	Gas Heating	Gas Heating	1	6	- 2,619.29	- 921.66	76.10	13.93	31.27	72.19
B19	Gas Heating	Gas Heating	1	10	- 2,793.60	- 856.27	86.68	15.86	35.62	68.53
B20	Gas Heating	Gas Heating	1	16	- 3,074.68	- 843.71	88.71	16.24	36.45	67.83
B21	Gas Heating	Gas Heating	2	0	- 2,777.45	- 1,632.01	33.13	6.58	17.83	106.01
B22	Gas Heating	Gas Heating	2	6	- 3,036.87	- 1,339.24	69.18	13.74	37.24	89.65
B23	Gas Heating	Gas Heating	2	10	- 3,184.67	- 1,247.34	80.51	15.99	43.33	84.51

B24	Gas Heating	Gas Heating	2	16	- 3,459.02	- 1,228.05	82.87	16.46	44.61	83.44
B25	Gas Heating	Gas Heating	3	0	- 2,866.00	- 1,720.55	34.27	8.47	21.99	103.70
B26	Gas Heating	Gas Heating	3	6	- 3,123.42	- 1,425.79	64.72	15.99	41.53	87.22
B27	Gas Heating	Gas Heating	3	10	- 3,255.75	- 1,318.41	75.80	18.73	48.64	81.23
B28	Gas Heating	Gas Heating	3	16	- 3,520.93	- 1,289.96	78.73	19.45	50.52	79.64
B29	Gas Heating	Gas Heating	4	0	- 3,381.97	- 2,236.52	34.75	7.57	25.23	130.80
B30	Gas Heating	Gas Heating	4	6	- 3,639.52	- 1,941.89	61.64	13.43	44.76	114.33
B31	Gas Heating	Gas Heating	4	10	- 3,763.60	- 1,826.27	72.19	15.72	52.42	107.87
B32	Gas Heating	Gas Heating	4	16	- 4,018.54	- 1,787.57	75.71	16.49	54.98	105.71
B33	Gas Heating	Heating Rod	1	0	- 2,418.77	- 1,236.19	38.94	8.29	18.49	85.57
B34	Gas Heating	Heating Rod	1	6	- 2,692.95	- 958.19	77.77	16.56	36.92	70.03
B35	Gas Heating	Heating Rod	1	10	- 2,868.52	- 894.06	86.75	18.47	41.18	66.44
B36	Gas Heating	Heating Rod	1	16	- 3,148.99	- 880.89	88.58	18.86	42.05	65.71
B37	Gas Heating	Heating Rod	2	0	- 2,846.12	- 1,663.55	40.33	9.10	24.51	103.21
B38	Gas Heating	Heating Rod	2	6	- 3,114.64	- 1,379.88	71.28	16.08	43.31	87.35
B39	Gas Heating	Heating Rod	2	10	- 3,265.15	- 1,290.69	81.01	18.28	49.22	82.37
B40	Gas Heating	Heating Rod	2	16	- 3,540.39	- 1,272.29	83.01	18.73	50.43	81.35
B41	Gas Heating	Heating Rod	3	0	- 2,929.98	- 1,747.40	39.55	10.74	27.73	101.28
B42	Gas Heating	Heating Rod	3	6	- 3,195.76	- 1,461.00	66.63	18.09	46.72	85.27
B43	Gas Heating	Heating Rod	3	10	- 3,331.42	- 1,356.96	76.45	20.76	53.60	79.46
B44	Gas Heating	Heating Rod	3	16	- 3,597.89	- 1,329.79	79.01	21.45	55.40	77.95
B45	Gas Heating	Heating Rod	4	0	- 3,452.67	- 2,270.10	40.53	9.79	32.46	127.75
B46	Gas Heating	Heating Rod	4	6	- 3,721.42	- 1,986.66	63.99	15.46	51.25	111.91
B47	Gas Heating	Heating Rod	4	10	- 3,850.76	- 1,876.30	73.11	17.66	58.55	105.75
B48	Gas Heating	Heating Rod	4	16	- 4,108.28	- 1,840.18	76.10	18.38	60.94	103.73

Table 19: Result Table II

	Annual Mileage BEV:		15,000 km							
Scenario #	Heating	Warm Water	Household [Pers.]	BES [kWh]	Annuity [€]	Annuity w/o Investment [€]	Self-Sufficiency Rate Electricity [%]	Self-Sufficiency Rate Energy [%]	Self-Consump-tion Rate [%]	CO_2 Equivalent [t]
C1	Heat Pump	Heat Pump	1	0	- 3,012.41	- 1,406.15	26.26	26.26	26.42	62.57
C2	Heat Pump	Heat Pump	1	6	- 3,279.38	- 1,120.93	45.05	45.05	45.33	46.63
C3	Heat Pump	Heat Pump	1	10	- 3,391.49	- 993.34	53.45	53.45	53.78	39.50
C4	Heat Pump	Heat Pump	1	16	- 3,582.77	- 890.98	60.19	60.19	60.56	33.78
C5	Heat Pump	Heat Pump	2	0	- 3,476.78	- 1,870.51	26.76	26.76	32.74	75.57
C6	Heat Pump	Heat Pump	2	6	- 3,754.92	- 1,596.47	41.60	41.60	50.90	60.25
C7	Heat Pump	Heat Pump	2	10	- 3,868.58	- 1,470.42	48.43	48.43	59.25	53.21
C8	Heat Pump	Heat Pump	2	16	- 4,043.31	- 1,351.52	54.87	54.87	67.13	46.56
C9	Heat Pump	Heat Pump	3	0	- 3,562.78	- 1,956.51	27.47	27.47	34.86	77.64
C10	Heat Pump	Heat Pump	3	6	- 3,842.70	- 1,684.25	41.68	41.68	52.91	62.43
C11	Heat Pump	Heat Pump	3	10	- 3,957.08	- 1,558.93	48.22	48.22	61.21	55.42
C12	Heat Pump	Heat Pump	3	16	- 4,126.50	- 1,434.71	54.71	54.71	69.44	48.48
C13	Heat Pump	Heat Pump	4	0	- 4,139.74	- 2,533.47	26.65	26.65	40.71	94.49
C14	Heat Pump	Heat Pump	4	6	- 4,435.27	- 2,276.82	37.79	37.79	57.72	80.15
C15	Heat Pump	Heat Pump	4	10	- 4,553.56	- 2,155.40	43.05	43.05	65.77	73.36
C16	Heat Pump	Heat Pump	4	16	- 4,715.06	- 2,023.27	48.79	48.79	74.53	65.98
C17	Gas Heating	Gas Heating	1	0	- 2,618.26	- 1,472.82	24.84	5.46	12.85	96.67
C18	Gas Heating	Gas Heating	1	6	- 2,878.29	- 1,180.66	62.30	13.70	32.21	80.34
C19	Gas Heating	Gas Heating	1	10	- 2,989.02	- 1,051.68	78.86	17.34	40.77	73.13
C20	Gas Heating	Gas Heating	1	16	- 3,241.91	- 1,010.94	84.07	18.49	43.47	70.86
C21	Gas Heating	Gas Heating	2	0	- 3,044.12	- 1,898.67	28.35	6.49	18.27	114.59
C22	Gas Heating	Gas Heating	2	6	- 3,299.96	- 1,602.33	58.83	13.46	37.91	98.03
C23	Gas Heating	Gas Heating	2	10	- 3,409.29	- 1,471.96	72.25	16.53	46.56	90.74

C24	Gas Heating	Gas Heating	2	16	- 3,638.42	- 1,407.45	78.87	18.05	50.82	87.14
C25	Gas Heating	Gas Heating	3	0	- 3,132.97	- 1,987.53	29.96	8.29	22.41	112.30
C26	Gas Heating	Gas Heating	3	6	- 3,387.92	- 1,690.28	56.31	15.58	42.11	95.68
C27	Gas Heating	Gas Heating	3	10	- 3,498.19	- 1,560.86	67.78	18.75	50.68	88.45
C28	Gas Heating	Gas Heating	3	16	- 3,708.35	- 1,477.38	75.16	20.79	56.21	83.79
C29	Gas Heating	Gas Heating	4	0	- 3,649.17	- 2,503.72	30.80	7.45	25.63	139.41
C30	Gas Heating	Gas Heating	4	6	- 3,904.78	- 2,207.15	54.42	13.17	45.29	122.83
C31	Gas Heating	Gas Heating	4	10	- 4,016.59	- 2,079.26	64.60	15.63	53.76	115.68
C32	Gas Heating	Gas Heating	4	16	- 4,212.19	- 1,981.21	72.40	17.52	60.25	110.21
C33	Gas Heating	Heating Rod	1	0	- 2,685.48	- 1,502.91	32.57	8.10	18.92	94.15
C34	Gas Heating	Heating Rod	1	6	- 2,953.19	- 1,218.43	65.04	16.18	37.78	78.25
C35	Gas Heating	Heating Rod	1	10	- 3,067.23	- 1,092.77	79.40	19.75	46.12	71.22
C36	Gas Heating	Heating Rod	1	16	- 3,320.64	- 1,052.54	83.97	20.88	48.77	68.98
C37	Gas Heating	Heating Rod	2	0	- 3,113.28	- 1,930.71	34.90	8.90	24.91	111.81
C38	Gas Heating	Heating Rod	2	6	- 3,378.13	- 1,643.37	61.59	15.70	43.95	95.75
C39	Gas Heating	Heating Rod	2	10	- 3,492.68	- 1,518.22	73.21	18.67	52.25	88.76
C40	Gas Heating	Heating Rod	2	16	- 3,723.96	- 1,455.86	78.99	20.14	56.37	85.28
C41	Gas Heating	Heating Rod	3	0	- 3,197.37	- 2,014.80	34.83	10.46	28.12	109.90
C42	Gas Heating	Heating Rod	3	6	- 3,460.60	- 1,725.84	58.56	17.58	47.27	93.75
C43	Gas Heating	Heating Rod	3	10	- 3,576.58	- 1,602.11	68.71	20.63	55.47	86.84
C44	Gas Heating	Heating Rod	3	16	- 3,789.18	- 1,521.08	75.36	22.63	60.83	82.32
C45	Gas Heating	Heating Rod	4	0	- 3,720.41	- 2,537.83	36.19	9.59	32.82	136.39
C46	Gas Heating	Heating Rod	4	6	- 3,987.23	- 2,252.47	57.05	15.12	51.74	120.44
C47	Gas Heating	Heating Rod	4	10	- 4,106.37	- 2,131.90	65.85	17.46	59.72	113.71
C48	Gas Heating	Heating Rod	4	16	- 4,305.96	- 2,037.86	72.72	19.28	65.95	108.45

Table 20: Result Table III

	Annual Mileage BEV:		20,000 km							
Scenario #	Heating	Warm Water	Household [Pers.]	BES [kWh]	Annuity [€]	Annuity w/o Investment [€]	Self-Sufficiency Rate Electricity [%]	Self-Sufficiency Rate Energy [%]	Self-Consump-tion Rate [%]	CO_2 Equivalent [t]
D1	Heat Pump	Heat Pump	1	0	- 3,279.77	- 1,673.50	24.10	24.10	26.81	71.19
D2	Heat Pump	Heat Pump	1	6	- 3,545.91	- 1,387.46	41.15	41.15	45.77	55.20
D3	Heat Pump	Heat Pump	1	10	- 3,656.88	- 1,258.72	48.82	48.82	54.30	48.01
D4	Heat Pump	Heat Pump	1	16	- 3,809.92	- 1,118.13	57.20	57.20	63.62	40.15
D5	Heat Pump	Heat Pump	2	0	- 3,744.56	- 2,138.30	24.89	24.89	33.10	84.21
D6	Heat Pump	Heat Pump	2	6	- 4,022.36	- 1,863.91	38.57	38.57	51.28	68.88
D7	Heat Pump	Heat Pump	2	10	- 4,135.46	- 1,737.31	44.88	44.88	59.67	61.80
D8	Heat Pump	Heat Pump	2	16	- 4,286.21	- 1,594.42	52.00	52.00	69.14	53.82
D9	Heat Pump	Heat Pump	3	0	- 3,830.71	- 2,224.44	25.60	25.60	35.21	86.29
D10	Heat Pump	Heat Pump	3	6	- 4,110.29	- 1,951.83	38.74	38.74	53.28	71.06
D11	Heat Pump	Heat Pump	3	10	- 4,224.30	- 1,826.14	44.79	44.79	61.61	64.03
D12	Heat Pump	Heat Pump	3	16	- 4,375.23	- 1,683.44	51.67	51.67	71.07	56.06
D13	Heat Pump	Heat Pump	4	0	- 4,408.09	- 2,801.82	25.12	25.12	41.04	103.16
D14	Heat Pump	Heat Pump	4	6	- 4,703.38	- 2,544.93	35.54	35.54	58.06	88.81
D15	Heat Pump	Heat Pump	4	10	- 4,821.59	- 2,423.43	40.47	40.47	66.11	82.02
D16	Heat Pump	Heat Pump	4	16	- 4,975.76	- 2,283.97	46.13	46.13	75.35	74.22
D17	Gas Heating	Gas Heating	1	0	- 2,884.63	- 1,739.18	21.35	5.41	13.30	105.23
D18	Gas Heating	Gas Heating	1	6	- 3,139.90	- 1,442.27	52.92	13.42	32.98	88.64
D19	Gas Heating	Gas Heating	1	10	- 3,243.48	- 1,306.15	67.43	17.10	42.01	81.03
D20	Gas Heating	Gas Heating	1	16	- 3,422.35	- 1,191.38	79.62	20.19	49.61	74.62
D21	Gas Heating	Gas Heating	2	0	- 3,310.88	- 2,165.44	24.91	6.40	18.70	123.17
D22	Gas Heating	Gas Heating	2	6	- 3,563.88	- 1,866.25	51.34	13.18	38.53	106.45
D23	Gas Heating	Gas Heating	2	10	- 3,670.52	- 1,733.18	63.09	16.20	47.35	99.01

D24	Gas Heating	Gas Heating	2	16	- 3,830.28	- 1,599.31	74.90	19.24	56.21	91.54
D25	Gas Heating	Gas Heating	3	0	- 3,400.03	- 2,254.58	26.72	8.12	22.82	120.90
D26	Gas Heating	Gas Heating	3	6	- 3,653.16	- 1,955.52	49.94	15.18	42.64	104.18
D27	Gas Heating	Gas Heating	3	10	- 3,761.76	- 1,824.42	60.11	18.27	51.32	96.86
D28	Gas Heating	Gas Heating	3	16	- 3,912.60	- 1,681.63	71.18	21.63	60.78	88.88
D29	Gas Heating	Gas Heating	4	0	- 3,916.45	- 2,771.01	27.74	7.34	26.03	148.02
D30	Gas Heating	Gas Heating	4	6	- 4,170.96	- 2,473.32	48.77	12.90	45.76	131.38
D31	Gas Heating	Gas Heating	4	10	- 4,281.03	- 2,343.70	57.92	15.33	54.34	124.14
D32	Gas Heating	Gas Heating	4	16	- 4,428.81	- 2,197.84	68.22	18.05	64.01	115.99
D33	Gas Heating	Heating Rod	1	0	- 2,952.27	- 1,769.70	28.16	7.92	19.35	102.74
D34	Gas Heating	Heating Rod	1	6	- 3,215.37	- 1,480.61	56.06	15.77	38.50	86.58
D35	Gas Heating	Heating Rod	1	10	- 3,323.98	- 1,349.51	68.72	19.33	47.20	79.25
D36	Gas Heating	Heating Rod	1	16	- 3,505.27	- 1,237.17	79.55	22.38	54.64	72.98
D37	Gas Heating	Heating Rod	2	0	- 3,380.50	- 2,197.92	30.87	8.71	25.31	120.42
D38	Gas Heating	Heating Rod	2	6	- 3,642.43	- 1,907.67	54.34	15.34	44.55	104.20
D39	Gas Heating	Heating Rod	2	10	- 3,755.09	- 1,780.63	64.61	18.23	52.96	97.10
D40	Gas Heating	Heating Rod	2	16	- 3,920.10	- 1,652.00	75.00	21.17	61.48	89.92
D41	Gas Heating	Heating Rod	3	0	- 3,464.81	- 2,282.24	31.21	10.20	28.50	118.53
D42	Gas Heating	Heating Rod	3	6	- 3,726.34	- 1,991.58	52.30	17.09	47.77	102.28
D43	Gas Heating	Heating Rod	3	10	- 3,840.72	- 1,866.25	61.39	20.06	56.07	95.28
D44	Gas Heating	Heating Rod	3	16	- 3,996.84	- 1,728.74	71.37	23.32	65.18	87.59
D45	Gas Heating	Heating Rod	4	0	- 3,988.19	- 2,805.62	32.75	9.41	33.18	145.03
D46	Gas Heating	Heating Rod	4	6	- 4,253.87	- 2,519.11	51.50	14.79	52.17	129.02
D47	Gas Heating	Heating Rod	4	10	- 4,371.40	- 2,396.94	59.49	17.09	60.27	122.19
D48	Gas Heating	Heating Rod	4	16	- 4,526.30	- 2,258.20	68.57	19.69	69.46	114.44

Table 21: Result Table IV

4 Research Paper 4 – Life Cycle Assessment of Residential Photovoltaic and Battery Systems for Private Prosumers

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Abstract

As measures against climate change, many countries – including Germany – have set ambitious targets for the reduction of greenhouse gas emissions. One possible avenue that might contribute to meeting these targets is the decentralisation of the power generation and storage by private prosumers, i.e. those individuals who have the roles of producers and consumers in the energy market. In this context, we investigate the extent to which such prosumers are actually able to reduce greenhouse gas emissions and also what other environmental impacts are concerned by the decentralisation of the energy market.

For our study, we have employed the recognised methodology of Life Cycle Assessment to determine the environmental impacts caused by the combined use of photovoltaic and battery storage systems. We have compared various combinations with the exclusive use of electricity from the public grid. To do so, we have developed a model in which we have combined LCA data from previous studies, including batteries for electric vehicles. In this way, we have been able to determine the environmental impacts in different categories that are caused by private prosumers.

We have found in terms of greenhouse gases that the use of photovoltaic systems adds value and that a battery storage system also reduces these emissions on average. In other impact categories, however, there are significant additional burdens, which must be weighed against the aforementioned savings in any overall assessment.

Keywords

Life Cycle Assessment; Prosumer; Photovoltaic; Battery Storage; Energy Transition

4.1 Introduction

4.1.1 Motivation and Background

In the context of climate change mitigation, Germany has set various interim targets, such as reducing greenhouse gas emissions by 40% by 2020 compared to the year 1990. By 2030, a reduction of at least 55% and by 2050 a reduction of 80-95% is targeted, in each case compared with the base year 1990. These targets have been derived from the UN Framework Convention on Climate Change and from EU agreements, among others, and are bindingly regulated in the country's Federal Climate Change Act of December 2019 [1, 2].

One important sector where far-reaching changes are needed is the energy sector. In addition to restricting CO_2-emitting electricity generation, Germany has also decided to renounce its nuclear power generation in the future. In 2011, the German government decided to completely terminate nuclear power generation in Germany by the end of 2022 [3]. However, following Russia's invasion of Ukraine, in October 2022, the German Chancellor announced that Germany would keep its last three nuclear power plants in operation until April 2023 due to the collapse in energy supplies from Russia and a decline in the nuclear power supply from France [4, 5]. Furthermore, on 29 January 2020, the cabinet of the German Federal Government approved a draft law on the phase-out of coal-based electricity generation. This bill defines the German coal phase-out for 2035 potentially, and definitely for 2038 at the latest [6].

These decisions, combined with Germany's ambitious GHG emission targets, require comprehensive changes in the country's power generation. One part of the solution is the decentralisation of renewable power generation and the associated promotion of so-called prosumers [7]. In general, a prosumer is an individual who both consumes and generates electricity for self-consumption and who feeds excess electricity into the grid [8]. In addition to the generation itself, storage or load can be utilised to make better use of self-generated electricity [9]. Usually, private prosumers are households that generate electricity via a photovoltaic (PV) system; a battery energy storage (BES) system is then used as a storage device [8, 10].

For more than 20 years, the development of prosumers in Germany has been supported by a guaranteed feed-in tariff for residential PV owners within the framework of the Renewable Energy Act (Erneuerbare-Energien-Gesetz; EEG) [11]. Even though the feed-in tariff has fallen steadily over time (see Figure 38), the capacity of installed PV systems has risen continuously (see Figure 39). In the private sector, previous studies have shown that the installation of a private PV system pays off financially despite the falling feed-in tariffs [12]. Since 2013 the number of BES systems installed in addition to PV systems in the private sector has been rising steadily as well [13]. While these investments have received governmental subsidies, a financial added value cannot be achieved under the given market conditions by using BES [12, 14]. Nevertheless, the cumulative capacity of BES in Germany continues to rise, a fact that can be explained by non-financial motives. For example, many households with a PV system aim to consume as much of their own electricity as possible, also in order to contribute to the climate protection goals mentioned above and not just to optimise the financial consequences [7]. Energy autarchy is another motive which has become even more relevant since Russia's invasion of Ukraine [15].

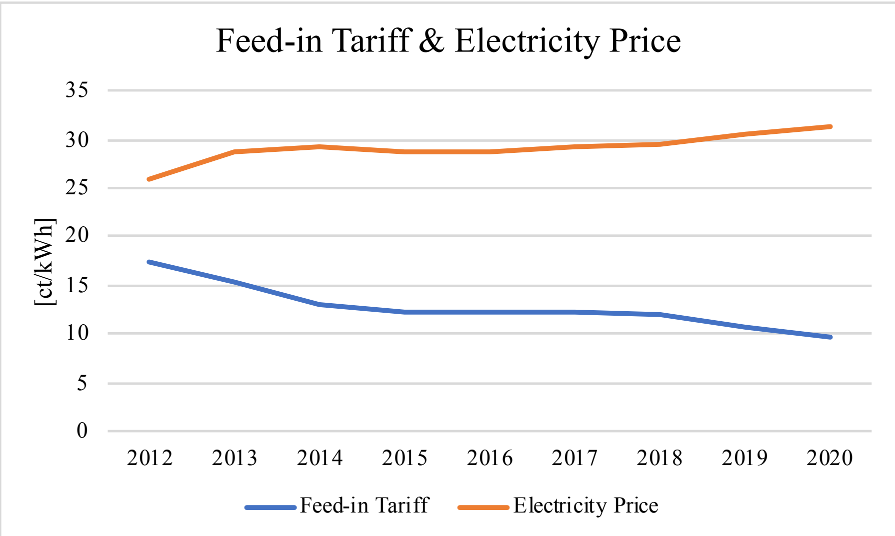

Figure 38: Development of the Feed-in Tariff and the Average Electricity Price in Germany [16, 17]

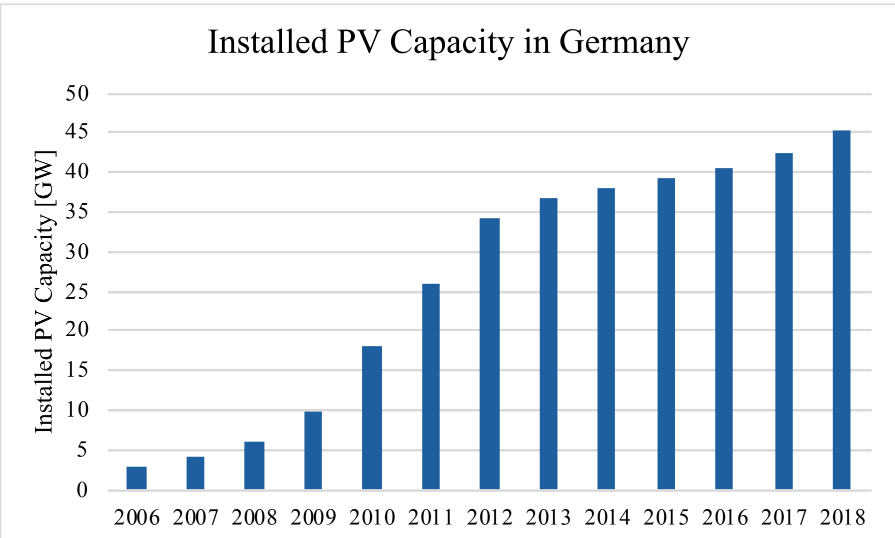

Figure 39: Installed PV Capacity in Germany over the Years [18]

The financial aspects of the private prosumer have already been examined in detail, including the possibilities of sector coupling [19]. In the present study, we analyse the extent to which the private prosumer can actually contribute to the achievement of climate protection goals. While the above-mentioned targets focus exclusively on greenhouse gas emissions, we now use the concept of Life Cycle Assessment (LCA) to assess the environmental impact regarding other impact categories in addition to the Global Warming Potential (GWP), which measures greenhouse gas emissions. We also consider the recycling of the PV system and the BES after their useful lifetimes. This last topic has so far received limited attention in the public debate, but in the future it will become very relevant due – among other things – to the expected high number of batteries from battery-powered electric vehicles and other devices [20, 21].

4.1.2 Existing Literature

Following thorough research, we failed to find any study that, with the use of LCA, comprehensively examines a private prosumer household with regard to its environmental impacts. Therefore, we concentrate on reviewing the literature on studies of separate assets, such as the production of a PV system or the end-of-life treatment of BES devices. In accordance with the objective of our study, we collected individual items, processed them and combined them into an overall picture.

The reviews [22, 23] in the area of environmental impacts of PV systems show that independent studies have arrived at comparable results, but these studies are usually limited to the consideration of the so-called energy payback time (EPT), i.e. the time it takes for a PV system to produce the energy that is needed for its own production. The GWP balance has also been examined. The consensus of the studies is an EPT of 1 to 3 years, with a clearly positive GWP balance in all cases.

During our research we found a few studies that present more comprehensive LCAs of PV systems with respect to several impact categories and we have directly incorporated them into our work: Alsema and De Wild-Scholten (2006) [24] compiled the first reliable LCI databases for PV module manufacturing by conducting a case study with 11 PV manufacturers from the USA and Europe. Based on their own data, they determined an energy payback time for PV modules of about two years and pointed out significant savings in CO_2 emissions compared to conventional energy sources. Fthenakis and Kim (2011) [25] investigated four commercial PV technologies and delivered detailed descriptions of the material and energy flows of these devices. De Wild-Scholten (2013) [26] updated data from Alsema and De Wild-Scholten (2006) [24] and determined energy payback times from one to two years and a carbon footprint of 20-81 CO_2-eq/kWh. Fu, Liu and Yuan (2015) [27] and Chen et al. (2016) [28] each delivered a comprehensive LCA of PV systems describing material and energy flows in the manufacturing process and presenting resulting environmental impacts in common impact categories. In chapter 4.2.3 we explain the exact use of the results presented there.

Despite the End-of-Life (EoL) phase being usually considered in an LCA, the final disposal of the PV system is not considered in any of the studies mentioned above. However, this topic will become increasingly relevant in the future. Based on the number of PV systems already installed and the expected further development, up to 10 million tons of PV panels to be disposed of can be expected by 2050. This number underlines the importance of adequate recycling. However, only the study by Latunussa et al. (2016) [29] has investigated the PV recycling process using an LCA.

The reason for the lack of LCA studies on prosumers is believed to be the insufficient amount of data in the BES area. For our studies we refer to LCA studies on batteries of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) for data acquisition, respecting the technical differences. The review by Peters and Weil (2018) [30] provides a good overview of the various studies in this field. Based on this, we have identified the studies by Zackrisson, Avellán and Orlenius (2010) [31], Majeau-Bettez, Hawkins and Strømman, (2011) [32], Ellingsen et al. (2014) [33] and Kim et al. (2016) [34] as a valuable basis for our own study. The specifics regarding the adaptation of the data to our application case are discussed in chapter 4.2.3.

Similarly to the field of PV systems, the recycling of batteries has yet to be considered in most studies. However, we have found one relevant study by Cusenza et al. (2019) [35] for reference. Assessing the EoL phase, they consider both the recycling process itself and the credits resulting from the reusability of extracted resources.

4.1.3 Contribution

As described above, we address the research gap where, based on the LCA methodology, no overall picture has yet been created that has holistically analysed the combined assets of a private prosumer. Therefore, we consider the following research question in our study:

Research Question

Can a domestic household reduce its environmental impact from electricity consumption by using a photovoltaic system in combination with a battery energy storage system?

For this purpose, we have developed a model that, for the first time, combines the results and findings of various LCA studies on PV systems and battery storage with the results of previous research on the financial room for manoeuvre and the self-sufficiency of private prosumers. Specifically, we have investigated the extent to which prosumers can generate via their assets an added value – in terms of various environmental impact categories during the use phase – which exceeds the impacts resulting from the production and recycling phases (Figure 40).

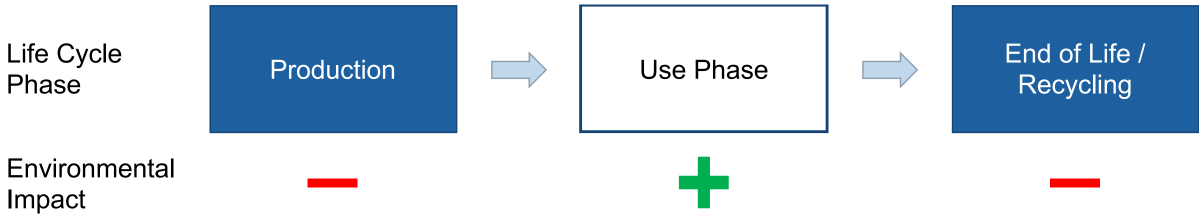

Figure 40: Schematic Environmental Impacts of PV and BES During Overall Life Cycle

Overall, we provide a sound basis for a politically, socially and economically important topic which is relevant to both political and private decision-makers. Thus, we provide a more differentiated fundament and want to initiate further research that will address technical developments in the field of private energy consumption and generation from an LCA perspective.

This paper is structured as follows: Chapter 4.2 discusses the LCA methodology and our way of applying it. Furthermore, it presents the aim and the structure of our model and describes the database. Chapter 4.3 presents the results of our calculations, including varied input variables and sensitivity analyses. Chapter 4.4 summarises and discusses the results.

4.2 Methods

4.2.1 LCA Methodology

The procedure for this work follows the recognised concept of Life Cycle Assessment (LCA) as defined in ISO 14040 [36] and ISO 14044 [37]. An LCA is a technique used to determine the various environmental impacts of a product throughout its overall life cycle, from production through all aspects of use to disposal. ISO 14044 provides a basic procedure for this, but not an exact description. According to Figure 2 1, there are four stages in the preparation of an LCA:

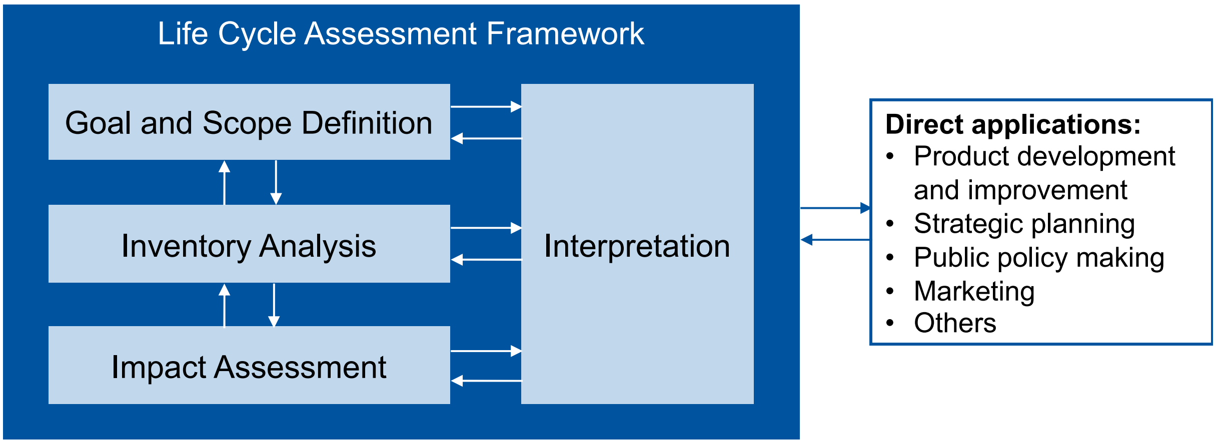

Figure 41: Structure of the Life Cycle Assessment Methodology [36]

Step 1 “Goal and Scope Definition” defines the exact object of consideration of the LCA. In addition, it describes the steps of the product life cycle to be considered and defines a functional unit related to the results. Chapter 4.2.2 tackles this topic, and it presents the structure of the considered scenarios.

Step 2 “Life Cycle Inventory Analysis” (LCI) describes all relevant material and energy flows of the product system. In particular, this includes the interaction with the environment: the extraction of raw materials and the release of emissions.

Step 3 “Life Cycle Impact Assessment” (LCIA) evaluates the material and energy flows determined in the LCI according to their environmental impacts in various categories. Steps 2 and 3 are carried out in chapter 4.2.3. Here, we look at the factors chosen to influence the material and energy flows, and how to deal with the various data sources used.

Step 4 “Interpretation” presents the results of the LCA, examines their robustness (often through sensitivity analyses), and allows critical interpretations. Chapter 4.3 provides these results and the corresponding sensitivity analyses, as well as their interpretation of both. A comprehensive evaluation of the results including the derivation of decision guidelines is presented in chapter 4.4.

4.2.2 Goal and Scope of Definition: Calculation Model

The aim of our study is to measure the environmental impact of the electricity consumption of private households. It compares the exclusive consumption of electricity from the public grid with the additional operation of a PV system and an optional BES system. For this purpose, the scope of the study is shown in Figure 42. The effects of the specific use of electricity, such as smart metering, are not explicitly considered.

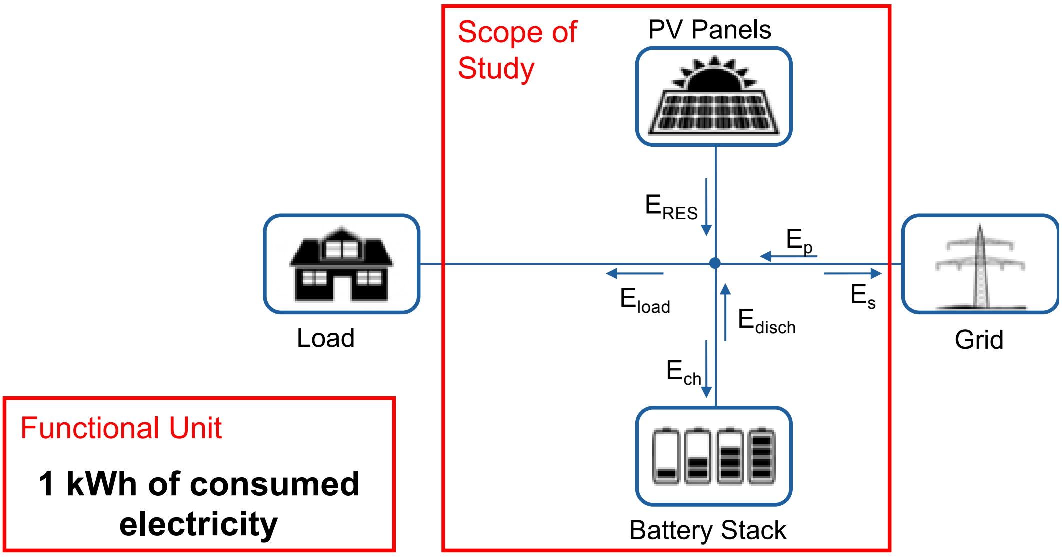

Figure 42: Scope of Study and Functional Unit

We have chosen 1 kWh of electricity consumed by the prosumer as the functional unit (FU) for the LCA study. The prosumer does not only consume electricity generated by their own facilities, but also draws electricity from the grid and feeds it into the grid. Therefore, if the prosumer is to be evaluated as a whole, it is more appropriate to consider the consumed electricity (both self-generated and from the grid) than to focus solely on self-generated electricity. All calculated impacts are related to this FU. This choice of FU ensures comparability of the scenarios considered, both with each other and with other studies.

In order to draw a comprehensive picture and to reach clear conclusions, we employ the following constellations (see Figure 43). This constellation panel has already been successfully used in previous studies [12]. It provides values for self-sufficiency and is appropriate for the model design.

Household Size / *Yearly Electricity Demand*	PV System: no PV	PV System: 4.88 kW_p	PV System: 7.32 kW_p	PV System: 9.76 kW_p
1 Person *1714 kWh*	No Battery	Considered Battery Capacities: 0 kWh, 6 kWh, 10 kWh, 16 kWh		
2 Persons *2812 kWh*				
3 Persons *3704 kWh*				
4 Persons *4432 kWh*				
+ Variation of Electricity from the Grid				

Figure 43: Constellation Panel

The four household sizes correspond to the yearly electricity consumption and to the use of electricity purely from the grid (no PV). Three differently sized PV systems are examined. The PV systems can be equipped with no battery storage system or with one of three different sizes of system. These constellations ensure that we cover the real-world behaviour of most households (prosumers) sufficiently well, as the considered battery sizes represent almost all existing private systems in Germany [13]. For each constellation we have assessed the environmental impacts of both assets during their entire lifecycles, as these can be fully attributed to the prosumer and to the environmental impacts from the electricity drawn from the grid. For the PV system and the BES system, we have considered the emissions from raw material mining processes, transport within the supply chain and energy consumption, waste disposal and direct emissions occurring during the manufacturing processes, including those from the EoL processes. For the electricity drawn from the grid, our calculations reflect both an average mix as of today as well as future modifications in order to compare results based on current electricity generation with those based on expected future changes.

Environmental impacts can be measured in eleven specific impact categories: Climate Change, Ozone Depletion, Human Toxicity, Respiratory Inorganics / Particulate Matter, Ionizing Radiation, Photochemical Ozone Formation, Acidification, Eutrophication, Ecotoxicity, Land Use and Resource Depletion [38]. In our study we concentrate on those impact categories in which the relevant impacts are within the scope of our study. Thus, we have measured the environmental impacts in the following four impact categories:

Climate Change

The global warming potential of a unit of material or energy expresses how much this unit contributes to climate change. Global warming potentials for all significant greenhouse gases have been determined by the International Panel on Climate Change. Relying on these data sets is highly recommended. The related unit for the GWP is 'kg CO_2-equivalents' [38, 39].

Ozone Depletion

At an altitude of 20-25 km, stratospheric ozone (O_3) protects the earth's surface from harmful solar UV-B radiation [40]. The emission of ozone-depleting substances disrupts the chemical balance and destroys the ozone layer. Therefore, the World Meteorological Organization has assigned ozone depletion potentials to major ozone-depleting substances. The corresponding unit for ozone depletion potential (ODP) is 'kg CFC-11-equivalents' (trichlorofluoromethane) [38, 39].

Human Toxicity

Considering human toxicity, both the exposure to toxic substances and the effects of such exposure have to be evaluated. An example is that of potential damages to the neurological system due to exposure to heavy metals. The unit for human toxicity potential (HTP) is 'kg 1,4DCB-equivalents' (1,4-dichlorobenzene) [38, 39].

Acidification

Releasing acidifying substances into water or soil causes an increase in the acidity (concentration of H+ ions) of either. This can lead to negative effects on the environment, e.g. the death of fish in an acid lake. The unit related to acidification potential (terrestrial) (TAP) is [kg SO_2-equivalents] [38, 39].

4.2.3 LCI and LCIA

In the following, we describe the structure of our LCI model. The first step is to describe the underlying causal relationships and then to present the data used and the associated LCIA procedure. Our model distinguishes between the three phases of a life cycle: the production phase, the use phase and the end-of-life phase. Figure 44 shows the schematic structure of our model.

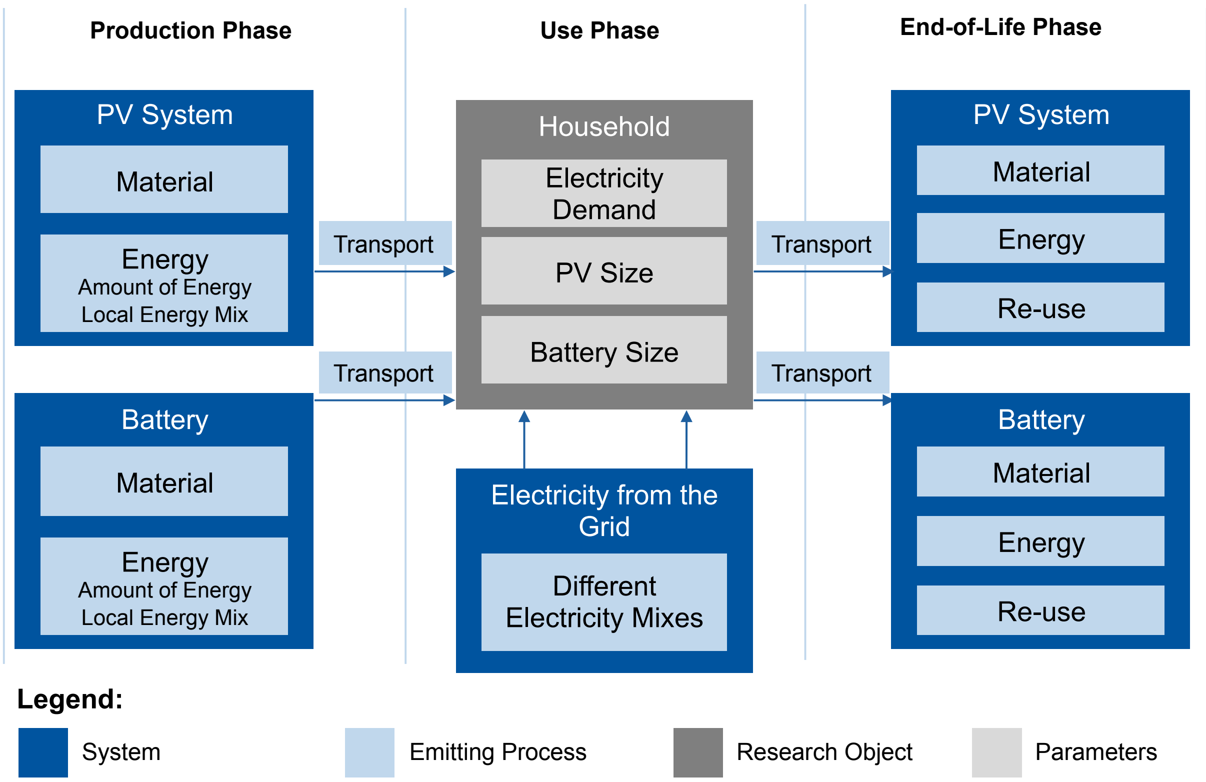

Figure 44: LCA Model Structure

Figure 45 explains the calculations of the emitting processes. It exemplarily illustrates the schematic production process of a PV system or a BES system with the corresponding emissions from the single sub-processes. The values used stemming from the emitting processes result from underlying sub-processes.

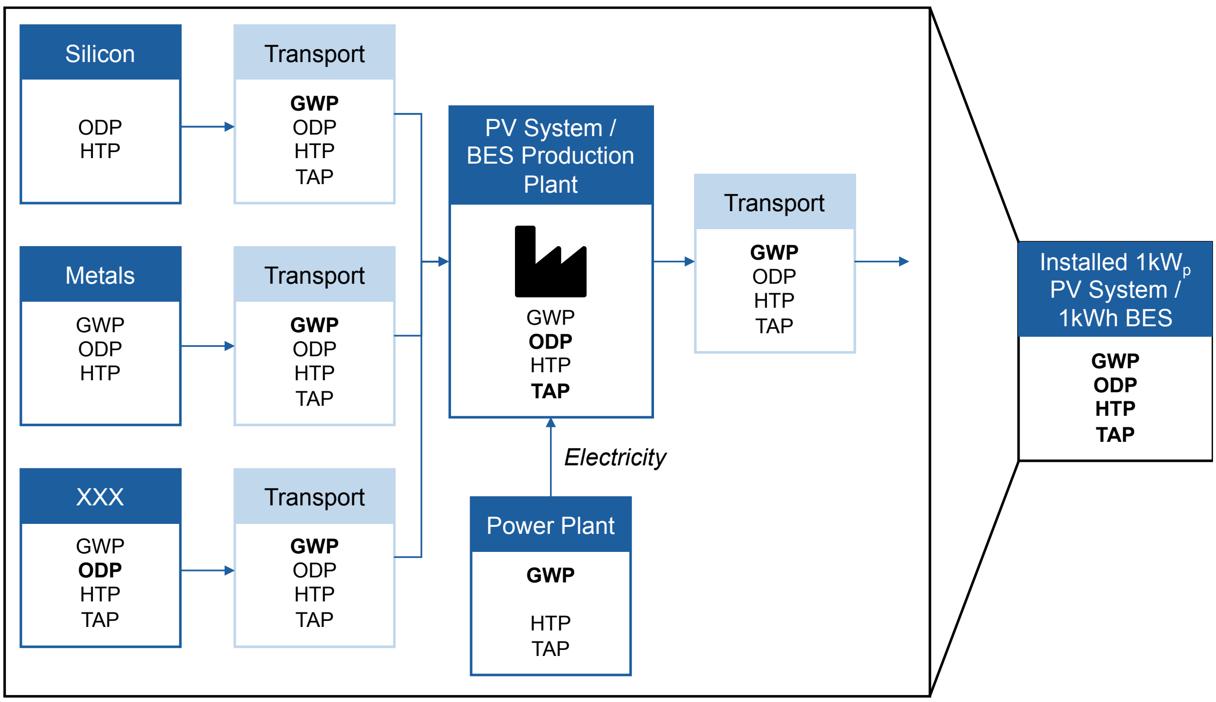

Figure 45: Exemplary Structure of the LCA of a PV System / a BES System

In our model, we consider the production phase of the PV system and the BES system. We determine the absolute emissions released by the material and energy consumption to produce the PV system ($E_{PVp,i}$) and the BES system ($E_{Bp,i}$). For this, we take into account the emissions from raw material mining processes, transport within the supply chain and energy consumption, waste disposal and direct emissions of the manufacturing processes. For the PV system, the results are related to a production capacity of 1 kW$_p$ and for the BES system to a storage capacity of 1 kWh.

The procedure for the end-of-life phase is similar and also involves the PV system and the BES system. Here, we take into account the emissions from transport within the supply chain and energy consumption, waste disposal, and direct emissions of recycling stage. In addition, it is also necessary to consider environmental benefits for recycling materials, i.e. emissions which would occur during the production and the mining of primary resources. These emission savings are included in the calculations as negative emissions. Again, we determine absolute emission values for the end-of-life phase for a PV system with a production capacity of 1 kW$_p$ ($E_{PVr,i}$) and for a BES system with a storage capacity of 1 kWh ($E_{Br,i}$).

In order to relate the values described above to the functional unit of the LCA study – 1 kWh of electrical energy consumed by the household – the absolute emission values are divided by the annual electricity consumption of the household (d_h) and the respective assumed lifetime (T_{PV}/T_B) and multiplied by the respective PV system size (s_{PV}) and battery size (s_B).

Regarding the use phase, the electricity drawn from the public grid is relevant when calculating the emissions. For this purpose, the emission values of the different types of electricity generation ($e_{k,i}$) in the electricity mix are multiplied by the respective planned share (m_k). The sum of these emissions from particular electricity generation types constitutes the emission load of one kWh from the public grid. This value is multiplied by the share of electricity drawn from the grid in relation to the total consumption of the household ($1 - a_{s_{PV},s_B,h}$).

The addition of the partial values described above yields the respective emission ($\bar{e}_{i,s_{PV},s_B,h}$) associated with the household's consumption of one kWh (FU). The dependencies described above lead to Equation 1; Table 22 gives an overview of the symbols used in the formula.

$$\bar{e}_{i,s_{PV},s_B,h} = \frac{E_{PVp,i} + E_{PVr,i}}{d_h * T_{PV}} * s_{PV} + \frac{E_{Bp,i} + E_{Br,i}}{d_h * T_B} * s_B + \left(1 - a_{s_{PV},s_B,h}\right) * \sum_{k=1}^{K} m_k * e_{k,i} \quad (1)$$

Formula Symbol	Explanation
$a_{s_{PV},s_B,h}$	Autarchy of household depending on household size h, s_{PV} and s_B
d_h	Yearly electricity demand of household size h
$E_{Bp,i}$	Emission i from production (material, energy, transport) of a 1 kWh BES system
$E_{Br,i}$	Emission i from recycling (material, energy, transport) of a 1 kWh BES system
$\bar{e}_{i,s_{PV},s_B,h}$	Emission i per kWh consumed by household depending on household size h, s_{PV} and s_B
$e_{k,i}$	Emission i of 1 kWh electricity from generation type k
$E_{PVp,i}$	Emission i from production (material, energy, transport) of a 1 kW_p PV system
$E_{PVr,i}$	Emission i from recycling (material, energy, transport) of a 1 kW_p PV system
m_k	Share of generation type k in electricity mix
s_B	Size of the BES system
s_{PV}	Size of the PV system
T_B	Lifetime of the BES system
T_{PV}	Lifetime of the PV system

Table 22: Overview of Formula Symbols

The evaluation of the production phase of the PV system is based on the data from Chen et al. (2016) [28]. Their study provides LCA data on the production of PV systems, considering the processes of infrastructure, raw materials, energy consumption, waste disposal, transport and direct emissions of manufacturing processes based on a detailed LCI analysis of material and energy requirements. In addition, their study incorporates the results of previous studies on this topic by Fthenakis and Kim (2011) [25], Alsema and De Wild-Scholten (2006) [24] and De Wild-Scholten (2013) [26]. The study by Fu, Liu and Yuan (2015) [27] helped to verify and complete any missing data for our study.

PV Prod. Phase	GWP [kg CO_2-eq]	ODP [kg CFC-11-eq]	HTP [kg 1.4DCB-eq]	TAP [kg SO_2-eq]
Impact per 1 kW_p	2.85E+02	6.28E-06	4.07E+01	1.67E+00

Table 23: LCA Data - PV Production Phase

For the EoL phase of the PV system, the recycling data were taken from the study by Latunussa et al. (2016) [29], which consists of an LCA data base for the EoL phase of PV panels. The article discusses the application of the LCA methodology to the process of recycling of PV waste panels. The related study provides a detailed process description containing all material and energy flows and complete input/output lists as well as a listing of environmental impacts per functional unit. To ensure that the data can be used in our work, we have transformed the study data from its weight-oriented reference value to the 1 kW_p generation capacity that we use.

PV EoL Phase	GWP [kg CO_2-eq]	ODP [kg CFC-11-eq]	HTP [kg 1.4DCB-eq]	TAP [kg SO_2-eq]
Impact per 1 kW_p	2.61E+01	1.66E-06	8.88E+00	9.13E-02

Table 24: LCA Data - PV EoL Phase

So far, there are no detailed studies available for BES systems used by prosumers which deliver information beyond the sole consideration of GWP. Therefore, we decided to use suitable LCA studies on batteries used in battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). Of course, technical differences between the battery types have to be considered. For example, BES do not require a cooling system, unlike the BEV/PHEV batteries, as they are exposed to different loads. Furthermore, when using BEV/PHEV data, attention must be paid to the functional units and parameters that are often vehicle-specific.

For the purposes mentioned above, the study by Majeau-Bettez, Hawkins and Strømman (2011) [32] fits best. This study contains detailed information regarding LCI, and the LCA results are also subdivided in such a way that the relevant components can be identified. The battery components considered are: Cell (anode cathode, separator, electrolyte and cell container), battery management system and packaging. As mentioned above, we transformed the data from the functional unit “50 MJ of electric energy to powertrain” to our reference unit “1 kWh of storage capacity” in order to ensure comparability and applicability in our model.

For the energy requirements of production, we used the frequently quoted data from Rydh and Sandén (2005) [41] and evaluated the energy consumption with the electricity mix described below [42].

BES Prod. Phase	GWP [kg CO_2-eq]	ODP [kg CFC-11-eq]	HTP [kg 1.4DCB-eq]	TAP [kg SO_2-eq]
Impact per 1 kWh	2.54E+02	1.96E-03	6.09E+02	1.54E+00

Table 25: LCA Data – BES Production Phase

For a complete life cycle assessment, it is also essential to consider the EoL phase of the battery. As already mentioned, there is no suitable literature on BES beyond regarding GWP. But even for BEV/PHEV batteries, articles by Zackrisson, Avellán and Orlenius (2010) [31], Majeau-Bettez, Hawkins and Strømman, (2011) [32], Ellingsen et al. (2014) [33], Kim et al. (2016) [34], Dai et al. (2019) [43] and Bhosale et al. (2022) [44] do not include the recycling process of batteries. Addressing this research gap, Cusenza et al. (2019) [35] published an article presenting an LCA for a BEV battery with a focus on the recycling process, which provides a data basis for further studies like ours. For this purpose, the authors disassembled a cell of an 11.4 kWh battery and used the resulting findings to create an LCI. Information about the battery management system, packaging and cooling (not relevant for BES) was taken from secondary literature. For the recycling process, they determined the additional environmental impacts and the benefits from the recyclable raw materials. When extracting their data, we made a transformation regarding the size of battery.

BES EoL Phase	GWP [kg CO_2-eq]	ODP [kg CFC-11-eq]	HTP [kg 1.4DCB-eq]	TAP [kg SO_2-eq]
Impact per 1 kWh	-9.84E+00	1.73E-06	-3.81E+01	-2.24E-01

Table 26: LCA Data – BES EoL Phase

For the use phase, the electricity drawn from the public grid must be evaluated. For this purpose, the shares of the individual types of generation must be determined and evaluated in terms of their environmental impact. Three constellations for the shares of the generation types have been provided for our calculations: the current electricity mix [42], an electricity mix for 2030 [45] and a transition scenario determined as the mean values of the other two constellations. Table 27 shows the values of the three constellations.

For the current electricity mix, we have used the average values from 2019 for Germany [42]. For 2030, we have chosen a distribution that can be expected for that year based on current political decisions [45]. This reflects, among other things, the phase-out of nuclear power generation and the agreed steps in the coal phase-out mentioned in chapter 4.1.

Type of Generation	Electricity Mix Germany 2019	Transition Scenario	Electricity Mix Germany 2030
Hydro Power	3.90%	3.72%	3.55%
Biomass – Maize	2.87%	2.17%	1.46%
Biomass - Manure	2.87%	2.17%	1.46%
Biomass – Organic Waste	2.87%	2.17%	1.46%
Wind - onshore	19.50%	23.69%	27.87%
Wind - offshore	4.00%	9.18%	14.36%
Solar	9.70%	12.20%	14.70%
Uranium	13.70%	6.85%	0.00%
Brown Coal – Rhineland	10.00%	6.82%	3.63%
Brown Coal - Lusatia	10.00%	6.82%	3.63%
Hard Coal	9.50%	8.04%	6.59%
Natural Gas	10.50%	15.81%	21.11%

Table 27: Scenarios of Electricity Mix [42, 45]

For the LCIA of the electricity mixes, we used the LCA program openLCA [46] to calculate the impact values on the basis of the database "ProBas" [47], published by the German Federal Environment Agency. For determining the share of externally purchased electricity, the assumed autarchy of a household is essential, depending on the number of persons living in the household, the size of the PV system and the size of the BES system. In a previous study we could already determine these autarchy values for the panel used (Table 28). Especially in the current time with rising energy prices and an announced increase in the risk of failures of the central power supply, the aspect of autarchy is coming to the fore for many prosumers. Nevertheless, the topic of autarchy itself with its monetary and non-monetary aspects is not in the focus of our study. The quantitative characteristic of autarchy varies with the variables PV system, battery and household size and in our study it is applied exclusively as an external input variable.

Household Size		PV System							
		no PV		4.88 kW_p		7.32 kW_p		9.76 kW_p	
		Battery	Autarchy	Battery	Autarchy	Battery	Autarchy	Battery	Autarchy
Household Size	1 Person	0 kWh	0%	0 kWh	47.37%	0 kWh	49.58%	0 kWh	50.83%
				6 kWh	86.20%	6 kWh	91.54%	6 kWh	94.80%
				10 kWh	87.36%	10 kWh	92.61%	10 kWh	95.83%
				16 kWh	88.16%	16 kWh	93.31%	16 kWh	96.53%
	2 Persons	0 kWh	0%	0 kWh	43.82%	0 kWh	46.79%	0 kWh	48.54%
				6 kWh	75.86%	6 kWh	82.84%	6 kWh	86.85%
				10 kWh	77.35%	10 kWh	84.79%	10 kWh	88.96%
				16 kWh	77.84%	16 kWh	85.67%	16 kWh	90.28%
	3 Persons	0 kWh	0%	0 kWh	41.40%	0 kWh	44.84%	0 kWh	46.87%
				6 kWh	69.03%	6 kWh	76.69%	6 kWh	81.18%
				10 kWh	70.63%	10 kWh	79.17%	10 kWh	84.08%
				16 kWh	71.45%	16 kWh	80.29%	16 kWh	85.43%
	4 Persons	0 kWh	0%	0 kWh	39.67%	0 kWh	43.41%	0 kWh	45.64%
				6 kWh	64.45%	6 kWh	72.41%	6 kWh	76.93%
				10 kWh	66.22%	10 kWh	75.08%	10 kWh	80.46%
				16 kWh	67.44%	16 kWh	76.24%	16 kWh	81.81%

Table 28: Panel with Autarchy Values

4.3 Results and Discussions (Interpretation)

4.3.1 Baseline Scenario

The results in this chapter are based on the assumption of a 20-year lifetime for the PV system, the BES system and the current electricity mix. The ratios of our results are similar for the different household sizes. Therefore, in this section we focus on the results for households with 1 and 4 persons to provide a comprehensive picture.

1-Person Household

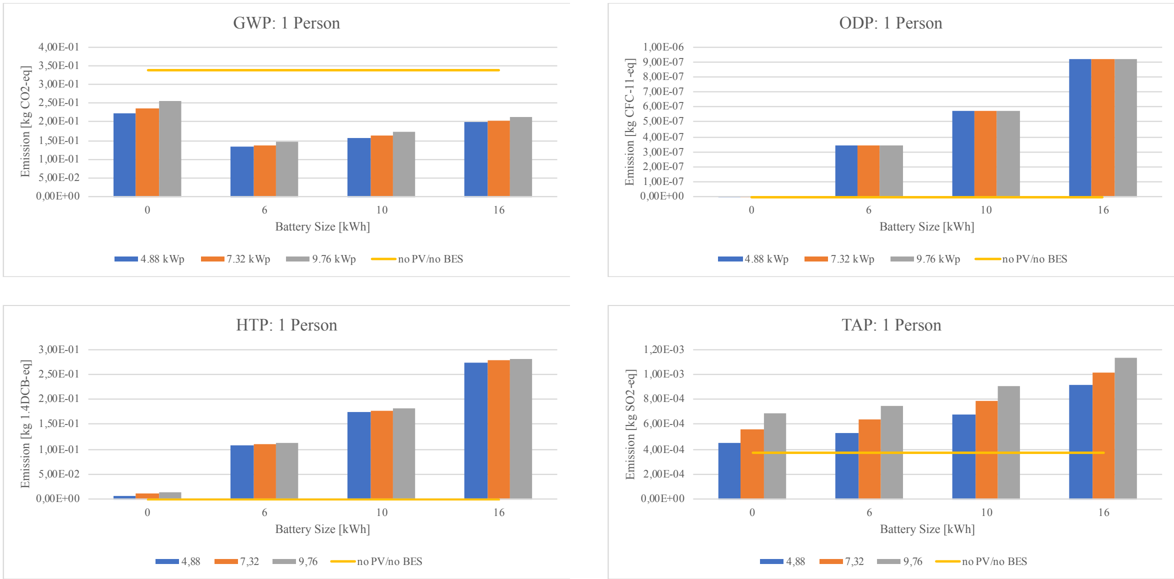

Figure 46: Results Baseline Scenario 1 Person

For one person, it can be concluded: in relation to the GWP, a PV system provides an added value. The additional use of a BES system further reduces emissions in the GWP impact category, with the smaller BES system (6 kWh) leading to the best result at this point. Since the smaller PV system also achieves the best result for this household size, the constellation of a 4.88 kW_p PV in combination with a 6 kWh BES system leads to the lowest GHG emission. With 1.34E-01 kg CO_2-eq per consumed 1 kWh, the impact in the GWP category in this constellation amounts to only 40% of the value without PV and BES (3.37E-01 kg CO_2-eq). The use of the PV system already leads to a reduction to 2.22E-01 kg CO_2-eq. Thus, GHG emissions can be successfully lowered by using PV in conjunction with BES.

For the impact categories ozone depletion potential (ODP) and human toxicity potential (HTP), the picture is quite the opposite. In both categories the constellation without PV and BES is the most advantageous one. In both categories it is apparent that a BES system is the driver of a higher impact in these categories. The impacts of the production phase and the EoL phase by far outweigh the savings in the use phase. For example, when operating a 7.32 kW_p PV system, the environmental impact in the HTP impact category increases tenfold from 1.09E02 kg 1.4DCB eq when supplemented by a 6 kWh BES system to 1.11E-01 kg 1.4DCB-eq.

The terrestrial acidification potential (TAP) shows a mixed picture. The constellation with the lowest environmental impact in this category is also the one without PV and BES, but the addition of a 4.88 kW_p PV system only increases the environmental impact from 3.74 kg SO_2-eq to 4.47 kg SO_2-eq. Furthermore, a further addition of a 6 kWh BES system to the “GWP optimum" also increases the environmental impact only to 5.33 kg SO_2-eq. As shown in Figure 46, a further increase in the size of both the PV and the BES system leads to further increases in the environmental impact in the TAP category.

4-Person Household

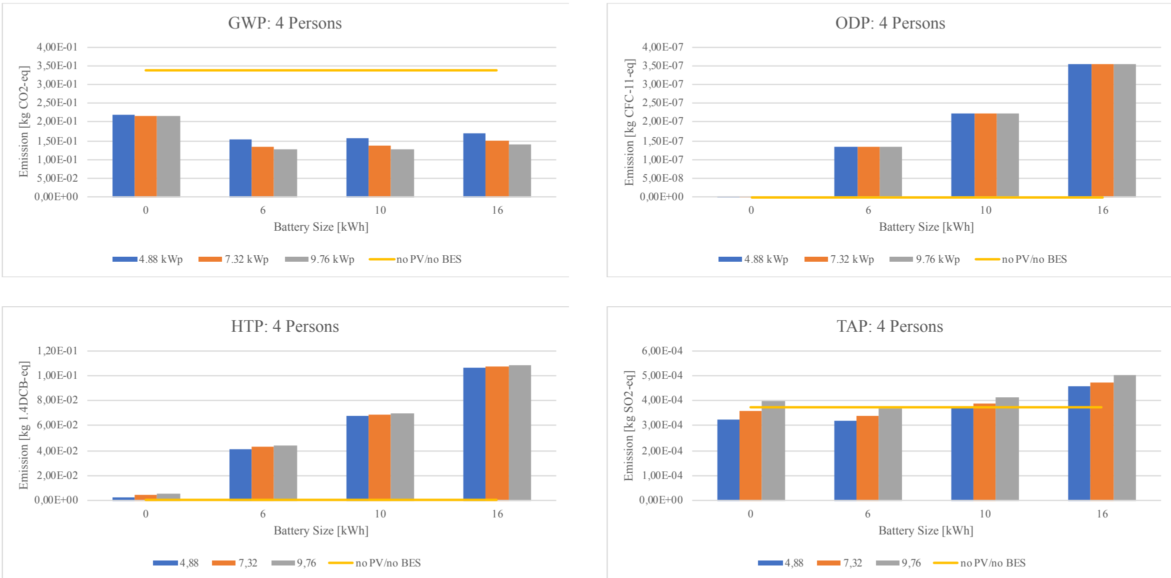

Figure 47: Results Baseline Scenario 4 Persons

As mentioned above, there is no fundamental change in the ratios of the results for the different household sizes considered. Nevertheless, deviations occur depending on the size of the household. Compared to the 1-person household described above, these deviations are most clearly visible in the results for the 4-person household (Figure 47) described below.

In the impact category GWP, a PV system is always advantageousness. Regardless of the size chosen and whether in combination with a BES system or not, the environmental impact is always reduced compared to the exclusive consumption of electricity from the grid, with a larger PV system always leading to a larger reduction. Solely using a 9.76 kW_p PV system leads to a reduction of the GWP environmental impact from 3.37E-01 kg CO_2-eq per consumed kWh (FU) to 2.18E01 kg CO_2-eq. The optimal constellation is achieved by supplementing the PV system with a 10 kWh BES system, reducing the environmental impact to 38% or to 1.28E-01 kg CO_2-eq respectively. It is important to note, however, that the differences between the BES sizes are small at this point. So even with a 6 kWh BES system, the environmental impact is reduced to 1.29E01 kg 1.4DCB-eq, which is important when evaluating the negative effects of an increased BES size.

For the impact categories ODP and HTP, the disadvantages of a PV system and especially of a BES system are also evident for a 4-person household. The most advantageous constellation regarding these two impact categories is the abandonment of PV and BES. Once again, a BES system is the driver for the pronounced environmental impacts. Here, the impacts from the production and EoL phase far outweigh the savings during the use phase again. In the HTP category, for example, when operating a 9.76 kW_p PV system, the addition of a 6 kWh BES system increases the environmental impact from 5.81E-03 kg 1.4DCB-eq to 4.43E-02 kg 1.4DCB-eq.

In the impact category TAP, there is a shift in the ratios for a 4-person household. The best constellation in this category is a 4.88 kW_p PV system in conjunction with a 6 kWh BES system, which has an impact of 3.19E-04 kg SO_2-eq. In principle, the effect increases with an increase in PV size but the constellation of a 9.76 kWh PV system and 6 kWh with 3.69E-04 kg SO_2-eq is still slightly more advantageous than the exclusive purchasing of electricity from the grid with 3.74E-04 kg SO_2-eq. The "GWP optimum" for a 4-person household (9.76 kW_p PV system; 10 kWh BES system) is slightly higher with 4.16E-04 kg SO_2-eq.

4.3.2 The Changing Electricity Mix

PV systems and BES systems can only provide environmental benefits over their entire life cycles if they reduce the share of electricity drawn from the grid and the associated impacts. Therefore, it must be examined as to what extent the benefits identified in the previous chapter will change if the applied electricity mix changes – as can be assumed for the future. For this reason, we will now analyse the effects of changing the electricity mix in favour of a higher share of electricity from renewable resources.

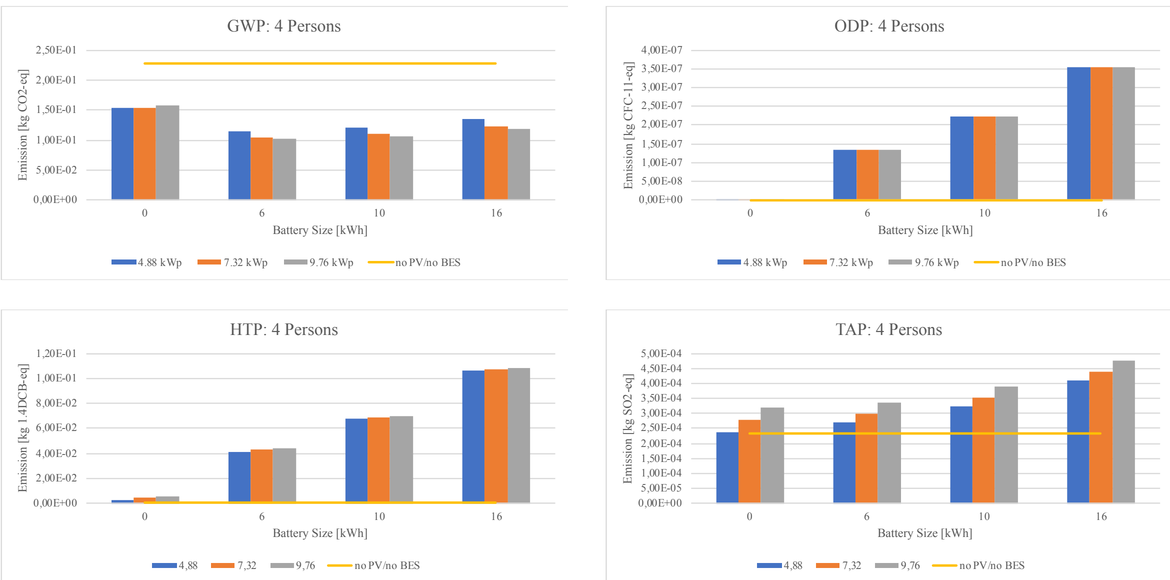

Figure 48: Results Future Electricity Mix 4 Persons

The change in the electricity mix drawn from the grid does not change the basic proportions and are similar to each other for the different household sizes. Therefore, we explain the existing changes using the example of a 4-person household (see Figure 48).

In relation to the GWP, there is a slight change due to the lower effect of grid electricity. The most advantageous constellation is a 9.76 kW_p PV system in conjunction with a now 6 kWh BES system. The advantages of this constellation compared to exclusive grid supply are still clear in this scenario. The impact of 2.28E-01 kg CO_2-eq is still reduced by 55% (instead of 60% previously) to 1.03E01 kg CO_2-eq.

For the impact categories ODP and HTP, the previous chapter has shown that the impact of the respective constellations is significantly driven by the size of the BES system. Given the comparatively small effect of the grid electricity, the change in the composition of the grid electricity has no notable effect in this respect.

For the impact category TAP, the change in the composition of the electricity from the grid causes slight changes in the ratios, which influence the advantageousness of the constellations among each other. The critical changes are: the smallest impact in the TAP category is achieved with the constellation of sole grid purchase (no PV; no BES). Furthermore, the addition of a BES system always increases the environmental impact. With today's electricity mix, PV systems in conjunction with BES systems can still achieve savings in the use phase that exceed the additional effects of the production phase and the EoL phase. The impact of the electricity mix assumed for 2030 does not enable this compensation, as the respective impact is much lower than with the current energy mix.

4.3.3 Sensitivity Analyses

With household size and changes in the electricity mix, we have already investigated two central components of our model. In addition, we have identified further factors that could have a major influence on the results of our calculations: the assumed lifetimes of the PV system and the BES system. We examine both factors in a short sensitivity analysis. One scenario assumes an extension of the lifetime of the PV system to 30 years (Figure 49), and another scenario a reduction of the lifetime of the BES to 10 years (Figure 50). 30 years are the maximum value used as a realistic lifetime of PV panels in literature [22, 23]. We also consider a reduction of the lifetime of the BES system, as disadvantageous charging and discharging cycles as well as environmental conditions, such as low temperatures, can reduce the lifetime of a BES system by up to half [48, 49].

First Sensitivity Analysis

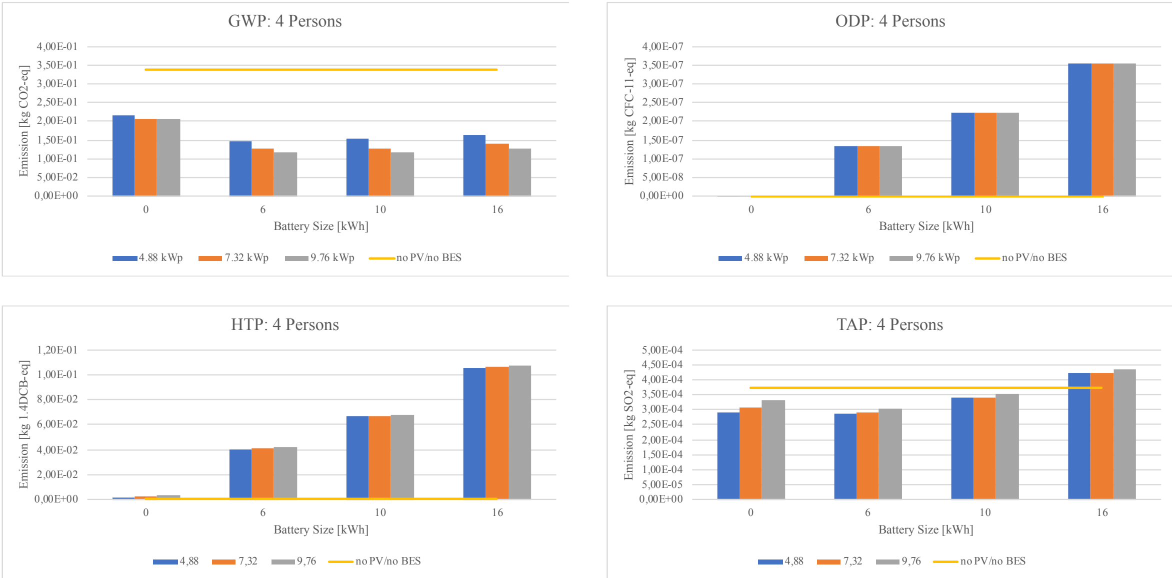

Figure 49: Results 1st Sensitivity Analysis 4 Persons

By extending the assumed lifetime of the PV system from 20 to 30 years, the proportions in our model do not alter the results much. The benefits remain qualitatively unchanged compared to the baseline scenario. The extension of the PV service life entails that the environmental impacts from the production phase and the EoL phase are distributed over more kWh (functional unit). As a result, the overall impacts per kWh decrease slightly in all impact categories, except for the exclusive consumption of electricity from the grid. As shown in the previous chapters, the size of the PV system used is not the determining driver in the different impact categories, so that the changes resulting from the lifetime extension are manageable.

Second Sensitivity Analysis

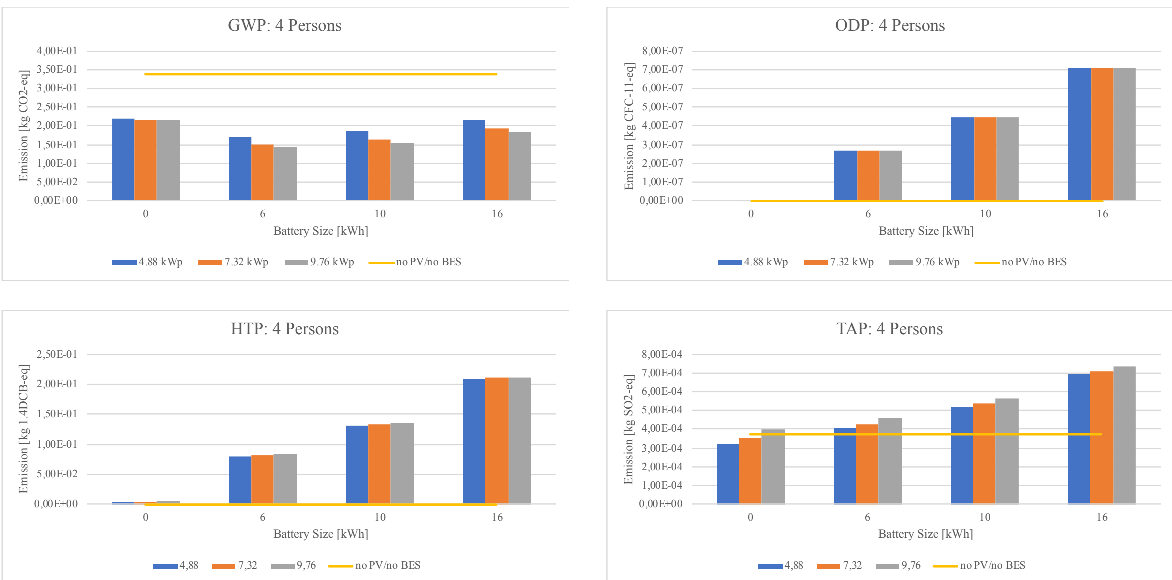

Figure 50: Results 2nd Sensitivity Analysis 4 Persons

In the impact category GWP, using a BES system in combination with a PV system remains advantageous even if its lifetime is halved. Although the difference between the impacts in the constellations with BES and those without becomes smaller and the most advantageous constellation is now a 9.76 kW_p PV system together with a 6 kWh BES compared to a 10 kWh BES system in the baseline scenario, all constellations with BES still remain below the constellations without BES with regard to their GWP impact.

In the impact categories ODP and HTP, the size of the BES system, as shown in the previous chapters, is the driver of the respective impact. Accordingly, the shortening of the lifetime of the BES system and the resulting distribution of the impacts from the production phase and EoL phase to less kWh leads to a significant deterioration of the impacts of the constellations with BES.

For TAP, the shortening of the lifetime of the BES system leads to slight changes in the relations. While the constellations of sole grid connection and a PV system without BES naturally remain unchanged, the effect in this category increases with increasing BES size. Using a 6 kWh BES system is no longer the best constellation in this category. However, the differences are small. The GWP optimum (9.76 kW_p PV; 6 kWh BES) with an effect of 4.59E-04 kg SO_2-eq is only slightly above the corresponding constellation without BES (9.76 kW_p PV; no BES) with 3.97E-04 kg SO_2-eq. Nevertheless, for larger BES systems the deterioration is more substantial.

4.4 Conclusions and Implications

In our study, we have conducted the first comprehensive LCA for the electricity consumption of a private prosumer, considering PV systems combined with BES. To this end, we have included and examined the state of research regarding LCA in the areas of PV and BES for both the manufacturing process and the recycling process, and we have combined the findings into a model that allows us to determine the resulting environmental impacts per kWh consumed by the prosumer for several reasonable constellations. This has enabled us to establish and analyse a constellation panel showing the environmental impacts for the selected scenarios which most realistically reflect market conditions and investment behaviours.

We have found that in the GWP impact category a household can indeed reduce its environmental impact by using a PV system combined with a BES system. While previous studies, which have examined the financial benefits of these assets, have only assessed the PV system positively, our study has also attributed added value to the additional use of BES in terms of the reduction of greenhouse gas emissions, and therefore GWP. However, this added value contrasts with a significant increase in the impact categories ODP and HTP, specifically caused by BES systems. For the TAP, the most advantageous constellations with regard to GWP lead to similar results as those for the conventional grid supply.

For future planning, it is important to understand that the qualitative relations do not change with regard to expected changes in the composition of the electricity mix. The positive contribution to GWP by private prosumers using PV systems in conjunction with BES systems will therefore be robust in the future. Even changes in the useful lifetimes of the PV system and the BES system, which can be considered as realistic, do not substantially change the observed results. Hence, the overall outcome of these results is very robust.

Different implications can be derived from our results. For political decision-makers, it is relevant that private prosumers with combined PV and BES systems are contributing to achieving GHG emissions targets. In this respect, governmental support can be justified. However, this contribution is “bought” at the expense of increased environmental impacts in other categories, which partly depend on the changing electricity mix from the public grid. At this point, it is recommended to create a balance between the extent of lowering GHG emissions and the additional impacts of other factors, and how this relates to other climate protection measures.

The outcome is similar for private decision-makers. The motivation of many prosumers to increase the self-consumption rate by using a BES system in order to create an ecological added value, even if this does not pay off financially, is justified in terms of GWP. However, the increased impacts in other categories should be taken into account, as the exclusive consideration of greenhouse gas emissions is too one-sided from an environmental point of view. Nevertheless, especially in times of increasing energy prices and uncertainties regarding grid reliability, many prosumers are aiming at a high level of autarchy for economic and also for non-monetary reasons.

As we have shown in our study, the LCA results should not be evaluated in absolute terms but rather in relation to each other. Moreover, the individual impact categories often conflict with each other. Many solutions intended to support the achievement of climate protection goals are publicly funded or involve other high (economic) costs. Therefore, it would be reasonable to investigate which solutions have the best ratio of costs and improvements in the impact categories in order to improve the effectiveness of public funding.

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