Economic, environmental, societal, and technological factors for the transition of the German energy system: A decentralized market perspective

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vorgelegt von

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Summary

The German energy transition is currently one of the major challenges for that country. To lower emissions and to slow down the climate change, a transition from fossil fuels to renewable energies can make a substantial contribution. In addition, more and more areas of the energy use are converted to electrical provisioning, for instance the share of electric or hybrid power trains in the mobility sector is increasing, but also the heating and the warm water supply in domestic households can be carried out with heat pumps. This situation leads to a higher demand for electricity which has to be generated renewably and distributed in the most efficient way to fulfil the emission targets of the EU and Germany for slowing down the climate change. The current organization of electrical power supply, including the structure of the grid as well as large power plants and market schemes have to be reorganized due to the changes that renewable electricity generation is bringing with it. Small, decentralized generation units are one of the most obvious of these changes. To analyse the challenges which come along with the energy transition, it is important to identify and analyse the causes and effects which have led to such a fundamental change. Since this change is not only a technological transformation but also a societal and economic transformation in favour of the environment, the causes and effects are various. This dissertation studies aspects such as self-sufficiency and CO_2 emissions in addition to a broader economic analysis.

The analysis of renewable electricity generation, storage and consumption in this dissertation is conducted in four steps. First, the history of the causes and effects of the different events concerning Germany’s energy supply is analysed to understand the combination of factors leading to the energy transition in Germany from the end of World War II until the Russian invasion of Ukraine in 2022. Second, the private prosumer, as a new actor on the energy market combining small-scale electricity generation and private consumption, is analysed from an economic perspective. In a third step, these analyses are extended with a deeper examination of sector coupling and CO_2 emissions. Fourth, the model of prosumers is evolved to become an energy community participating in energy markets. The energy community is investigated in the market environment under different considerations, such as participation in the balancing markets or different energy storage capacities.

Furthermore, the present dissertation consists of two parts. Part A provides an overview of the motivation for this thesis and the changes and consequences that the energy transition is bringing with it. The results of the four research papers are summarized and interdependencies

of the results, implications, and limitations are shown. Part B consists of the four research papers in detail.

Research paper 1 analyses the events which have ultimately led to the current state of legislation and the status quo of the energy transition in Germany. The events are clustered into the three pillars of sustainability: economy, environment, and society and politics. Furthermore, a fourth pillar – technology – is introduced. The events are analysed not only chronologically but also in the light of their causes and effects. The analysis shows how the different events supported each other and why operators of large power plants have been challenged by the energy transition.

Research paper 2 focuses on a new actor: the prosumer on a private household basis. New technical settings enable private customers to generate electricity, typically via rooftop photovoltaic (PV) systems. The installation of such systems was highly subsidized by the German regulation system and although the subsidies have decreased in the last years, privately owned PV systems are still supported. Additionally, research paper 2 analyses the ownership costs of a battery storage system. A scenario analysis investigates the economic differences between energy supply from the public grid and different sizes of PV and battery storage systems.

In research paper 3, the concept of the prosumer is deepened by adding additional energy demand for heating and warm water supply as well as an electric vehicle to the economic calculation for a prosumer. The concept of sector coupling is addressed in this research paper. The calculation assumes that more demand for electricity can make the concept of a prosumer economically more efficient. In various scenarios, different concepts of the prosumer are compared to conventional concepts of energy supply. Besides the economic evaluation, research paper 3 also calculates the CO_2 emissions for the different scenarios. The results of research paper 3 identify the barriers to the prosumer concept and the approvals needed to make this concept economical feasible and to support renewable energy generation and consumption.

In research paper 4, prosumers are aggregated into energy communities. On the one hand, prosumers in energy communities have more possibilities to share energy generation, storage or consumption schemes, and to lower transmission and distribution losses by raising the self-sufficiency rate within the energy community. On the other hand, energy communities, as assumed in research paper 4, can reach the critical generation and storage capacity required for energy market participation. In research paper 4, participation in the energy markets of the day-ahead-market on the SPOT market and participation in the market for secondary and tertiary control on the balancing market are taken into consideration. The simulation model analyses the financially most beneficial options for running an energy community.

In total, this dissertation not only provides an overview of the factors which have led to the introduction of the energy transition in Germany, and the interaction of this factors. It also evolves and analyses models for realising the energy transition. Therefore, economic analysis and technical feasibility are at the centre of investigation here. The results of this dissertation support decision makers on different levels. Private prosumers can see the economic impact of their investment; Energy communities are able to identify and assess their own risks; Regulators and political decision makers are able to derive decisions to support Germany's energy transition.

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List of Abbreviations

€	Euro
AE	Available Energy
AK	Available Capacity
AV	Average
BEPE	Break-even price of energy
BES	Battery Energy Storage
BP	Share of balancing power
C_{AL1}	§19-Levy
C_{AL2}	Levy for flexible demands
C_{AL3}	KWKG Levy (CHP)
C_{AL4}	Other costs
C_{AL5}	EEG-Levy
C_{AL6}	Electricity tax
C_{AL7}	Grid costs
C_{BP}	Costs for balancing power
C_{Capex}	Capital Expenditure
CE	Consumed energy
C_{Opex}	Operational Expenditure
C_{P}	Costs for trading licenses
CSR	Corporate Social Responsibility
ct	(Euro-)Cent
C_{TCOp}	Annual Prosumer-Oriented Total Cost of Ownership
D	Duration for Depreciation
DC	Direct Currency
DE	Demanded Energy
DSO	Distribution System Operator
EBIT	Earnings Before Interests and Taxes
EC	Energy Community
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act)
FEF	Fixed energy fee
FEP	Fixed energy price
FNA	Federal Network Agency (Bundesnetzagentur)
GDP	Gross Domestic Product
GW	Gigawatt
HV	High Voltage
i	Discount Rate
INV	Investment
INV_{BES}	Investment for BES-System
INV_{PV}	Investment for PV-System

KfW	Kreditanstalt für Wiederaufbau
kW	Kilowatt
kWh	Kilowatt Hour
kWp	Kilowatt Peak
LNG	Liquid Natural Gas
LV	Low Voltage
MV	Medium Voltage
MW	Megawatt
n	Number of trading time slots
NCF	Net Cash Flow
NGO	Non-Governmental Organization
NPP	Nuclear Power Plant
NPV	Net Present Value
OTC	Over the counter
PHC	Power-heat coupling
PJ	Petajoule
PP	Power Price
PV	Photovoltaic
RES	Renewable Energy Systems
RP	Research paper
SE	Sold Energy
t	Period
T	Period under Review
TCO	Total Cost of Ownership
TCO_P	Prosumer-Oriented Total Cost of Ownership
TSO	Transmission System Operator
TWh	Terrawatt Hour
UN	United Nations
VAT	Value-added tax
VBA	Visual Basics for Applications
VPP	Virtual Power Plant
WP	Energy Price

Part A. A Comprehensive Overview of the Dissertation

The present dissertation investigates the influences which are impacting on the German energy transition, and it performs an economic analysis from a decentralized market perspective. Therefore, new business opportunities are taken into consideration as well as subsidies and market opportunities in Germany. The dissertation is composed of two parts. Part A is a comprehensive overview of the dissertation. Part B comprises four papers which analyze the underlying research questions (analogous to Kappner (2023) [1]).

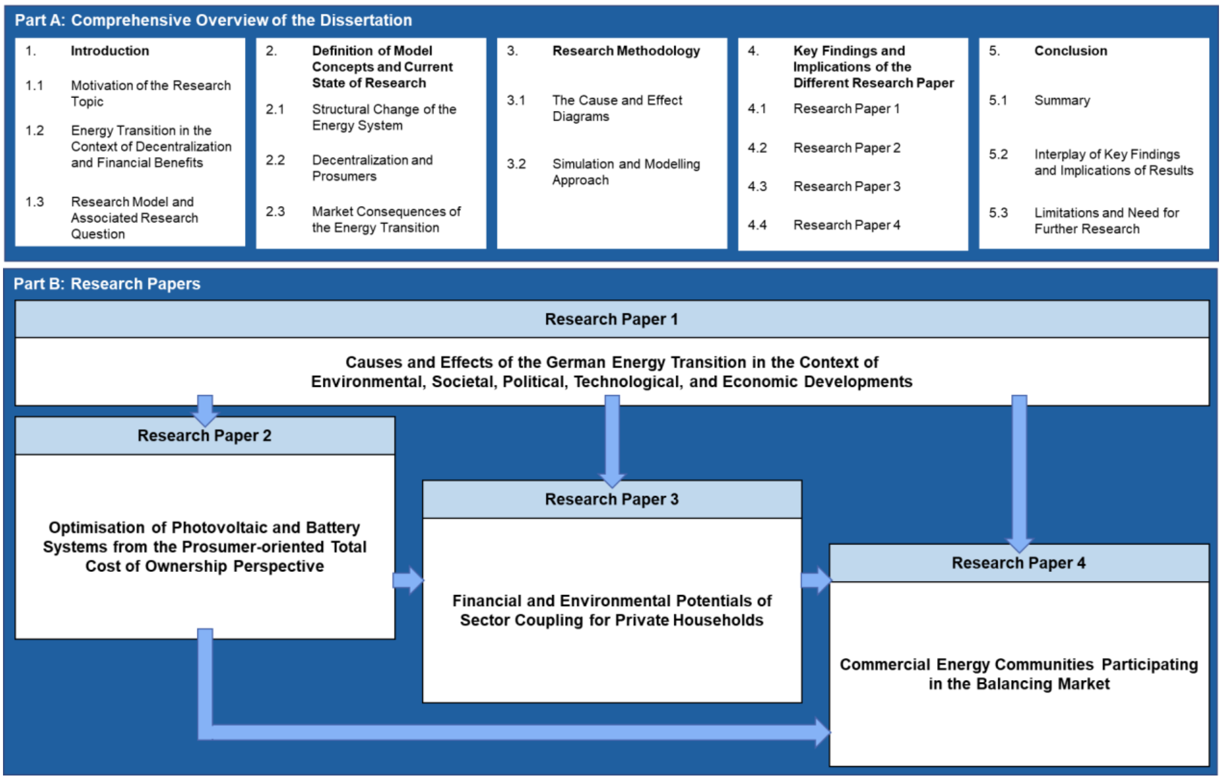

Figure 1: Overview of the two parts of the dissertation (based on Kappner (2023) [1] *and Suares (2019)* [2]*)*

In Part A – the comprehensive overview – a summary of the dissertation is given. Chapter 1 introduces the research topic. The motivation of the research topic is expressed in the first section from the perspective of sustainability and also from a technical perspective. An overview is presented of the decentralization of the energy generating infrastructure and the challenges associated with that process. Finally, in the last section of chapter 1, the research model and the overall research question as well as the individual research questions of the different research papers are derived. In chapter 2, the general model of this dissertation is introduced. Different layers of the model show the evolution of the research papers and how the papers are connected. Furthermore, the structural change of the energy markets and the consequences of this decentralization are presented. This leads to the specific focus on rising actors, such as prosumers or energy communities. In chapter 3, the used methodologies are explained. A detailed perspective on the simulated models is given, since the real data models are key for the validation of the results of the different research papers. Boundary conditions used in the research papers are explained and classified. The findings and implications of the different models are expressed in chapter 4. The content of the four research papers is taken up and the results are shown. Finally, chapter 5 sums up the findings of the different research papers and answers the overall research question. In this chapter, it is also described how the key findings of the different research papers interact with each other. Furthermore, theoretical and practical implications resulting from this dissertation are highlighted. In the last section of chapter 5, limitations and directions of further research are examined.

In Part B, four research papers are presented:

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	• Published in “Energy, Sustainability and Society” (2023) 13: 28. Springer Berlin Heidelberg [3] • Presented at the 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” (2019) 9: 44. Springer Berlin Heidelberg [4] • Presented at UFZ EnergyDays 2018 • Presented at the 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 the PhD Seminar of the Chair of Management Accounting, RWTH Aachen University
4	Commercial Energy Communities Participating in the Balancing Market	Letmathe, Weidinger	• To be submitted to “Futures” • Presented at the POMS 2019 • Presented at the PhD Seminar of the Chair of Management Accounting, RWTH Aachen University

Table 1: Research papers of the dissertation (analogous to Kappner (2023) [1]*)*

1 Introduction

The following section introduces the topic of Germany's energy transition and demonstrates the need for a changing infrastructure in energy deployment as well as in the country's market system. First, the research topic is introduced which leads to the use of renewable energy generation undertaken by small-scale generators, such as photovoltaics (PV) or wind turbines. Second, by using smaller generation units, the context of decentralisation and possibilities of financial benefit arising from the energy transition is introduced. In a third step, the overall research question, the used research model and the associated research questions answered in the research papers one to four, are shown.

1.1 Motivation of the Research Topic

Society in general has become more conscious of the climate crisis within the last years. Civic movements such as #FridaysForFuture have promoted the change towards renewable energy generation on a broad basis. However, the idea of limiting the use of resources was already taken up by the Club of Rome, which was founded in 1968 [5] and published its first report "The Limits to Growth" in 1972 [6]. Since then, politics have considered the need for an energy transition in some international contracts, such as the Kyoto Protocol [7] or the Paris Agreement [8]. Furthermore, national laws have been established to support renewable energy generation in Germany, such as the Energieeinspeisegesetz (Energy Conservation Act) in 1990 [9] or the Erneuerbare Energien Gesetz (EEG; Renewable Energies Act) in 2004 [10]. However, in 2018 the generation of one consumed kWh of electrical energy still emitted 473 g of CO_2 on average, in 2022 it still emitted 434 g/kWh CO_2 on average [11]. Next to the national goal of achieving climate neutrality by 2045 in Germany [12], the European Parliament in 2009 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" [13].

The quotation from the European Parliament indicates that many pathways need to be followed simultaneously in order to achieve the climate goals. However, different pathways are also being considered by different Member States. While Denmark has established a mainly decentralized grid with almost 100% renewable energy systems (RES) [14], France distributes, inter alia, electricity from nuclear power plants in a centralized grid [15]. In Germany, large power plants are also in use, but the generation from nuclear power plants decreased from

1,663 PJ in 1990 to 754 PJ in 2021 and the electricity generated from coal decreased from 3,066 PJ to 1,437 PJ during the same period [16]. On the other hand, the electricity generated from renewables increased from 122 PJ to 1,056 PJ from 1990 to 2021 [17]. Next to the expansion of renewable energy generation, the development of energy storage systems is supported by German politics [18] and nuclear power plants have been taken off the grid in 2023 [19].

While its support for energy storage systems is at a low level, the German government has heavily subsidized the installation of PV panels. Only 9% of the electricity supported by the EEG law was generated by PV in 2010. At the same time, PV was being subsidized with 40% of the incentives for renewable generation by the EEG [1, 4, 18], which makes PV a cost-intensive technology. Since then, the subsidies have decreased step by step and the efficiency of PV systems has increased [20]. But also, on the one hand, the European Commission described PV in 1997 as a leading-edge technology with high potential for exports in a very competitive global market [21]. On the other hand, the overall share of electricity generated with PV in Germany was 6.1% in 2017 [22]. These factors contribute to the fact that the electricity price in Germany is one of the most expensive in Europe, although the liberalisation of the electricity market system was introduced early on [23]. In summary, it can be stated that installing assets for electricity generation via PV systems is associated with high costs, but that PV systems are also perceived to be a technology with high potential. Furthermore, Stern (2007), analysed the overall costs of not acting and the risks of the climate change by using formal economic models, the calculations show a loss equivalent to at least 5% of the global GDP each year [24]. When using a wider range of risks and impacts, the estimation increases up to 20% of the GDP or more [24], which underlines the argument that even cost-intensive renewable technologies are economically feasible. Nevertheless, to establish a higher share of renewable generation systems, especially PV systems, the relationship between costs and financial outcome must improve.

Prosumers can respond to some of the identified challenges, since self-sufficiency will become more important in the future energy supply [25]. Thus, the decentralization of energy generation is analysed, which is one way to accelerate the energy transition and can offer economic, environmental and social benefits [26]. For some prosumers, decentralization can provide a disposable income [27]. Furthermore, decentralized energy systems can be interesting not only economically but also from a technological perspective [28], for example by providing energy in an islanded mode or to stabilize the distribution grid. And although the best deployment strategy for decentralized storage has not been identified yet [29], decentralized storage capacities are becoming key for compensating gaps between decentralized generation and local demand [28, 29].

This dissertation analyses the influences and their contexts which have led to the energy transition and provides new market models and business opportunities in decentralized generation, storage, and consumption. In the next section, decentralization and its benefits for prosumers are explained.

1.2 The Energy Transition in the Context of Decentralization and Financial Benefits

The energy transition has a major influence on economic decisions and a vital impact on the environment and society. Increasingly, general corporate decisions are also being linked to sustainability goals. New technical solutions play a role here, not only in the generation of electricity. These technical solutions accelerate or enable sustainable management. For the generation, distribution, and consumption of electrical energy, this means that decentralized technical solutions will become increasingly important in the future and that these new solutions must be economically viable. The success of the energy transition depends on the participation of energy producers, grid operators, and consumers. Their efforts must be dovetailed to achieve maximum progress [30–32].

Due to the technical conditions, it might not be possible to generate renewable electricity exclusively in central power plants in the future. PV systems and individual wind turbines must also be integrated into the grid. The nominal power of these plants is typically much lower than that of large fossil power plants, which additionally offers the possibility to integrate PV and wind power plants into the MV or LV grid. This leads to additional challenges for power grids. The structure of power supply changes from top-down to a mix of top-down and bottom-up [30]. In addition, PV systems and wind turbines are dependent on natural influences, i.e., the presence of relevant amounts of sunshine and wind. This results in greater volatility in the feed-in, in addition to the greater geographic distribution of generating units. These are two crucial technical challenges posed by the energy transition [27].

On the economic side, there are also restrictions and rules that can have a major influence on the success of the energy transition. In Germany, electricity generated from renewable sources must be fed into the grid as a priority [33]. This means that when there is a lot of sunshine or a lot of wind, there is also a lot of energy available. These very different amounts of electricity lead to strong fluctuations in prices on the energy market (see Figure 2) [34].

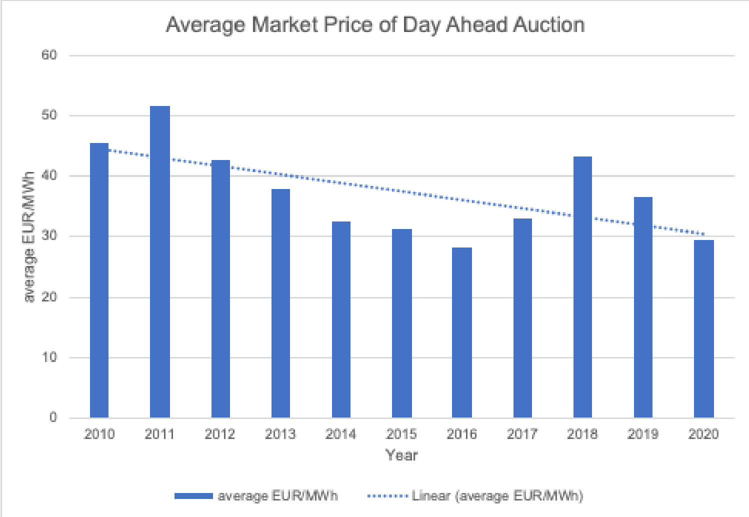

Figure 2: Average market price of day-ahead auction [34, 35, and research paper 1]

This is a disadvantage for large and sluggish generating units, such as lignite-fired power plants, because they can generate electricity continuously but cannot sell it at consistent prices. In addition, on average, prices for the day-ahead market on the power exchange are falling [35].

These factors are initially an advantage for renewable energy producers, since the variable and external costs per kWh generated are lower for PV or wind power plants than for plants in which fossil fuels are used to generate energy [36].

At first, the points addressed are an advantage for renewable energy producers. Nevertheless, decentralization and the high market price volatility also affect the operators of renewable plants. For the energy transition to succeed better, it is necessary that consumers are also integrated and, for example, roof areas are used for PV systems. Consumers thus become prosumers [27]. However, the investment costs for PV systems are high [37] and the subsidies per kWh fed into the grid were initially very high, but have been greatly reduced in recent years [38], even though there is still a fixed feed-in tariff per kWh for systems below 10 kWp [39]. Among other things, these incentives have led to the capacity of installed PV systems in Germany increasing from 0.114 GWp in 2000 to 59 GWp in 2021 [38, 40, 41].

The points described can lead to various problems that need to be countered in order to drive the energy transition forward. On the one hand, the fixed subsidies per kWh fed into the grid will eventually cease. In the medium term, therefore, solutions must be established that generate a profit even without subsidies, since otherwise no further investments in decentralized energy-generation systems are expected to be made. Furthermore, it is especially true for PV systems that they primarily generate electricity when all PV plants in the vicinity also generate electricity. This means that the most electricity is generated when the price on the electricity market is expected to be very low or even negative [34]. One solution could be to store the electricity or use it wisely at that time. This would suggest converting electricity it into thermal energy in heating systems, among other options.

However, if the electrical power is discharged through the distribution grid for storage or use, the grid may reach its transmission limits. This entails additional grid stabilization measures, which in turn come at a cost. These measures are also unlikely to have much effect on the market price, as there continues to be a lot of energy in the grid and so the price remains low. This reduces the prosumer's profit under market conditions.

For these reasons, it appears sensible that the electricity generated should be consumed or stored where it is generated. This means that prosumers could provide a greater benefit to themselves and the overall system if each of them had a storage facility, such as a battery. However, the investment costs for decentralized battery storage are high and the demand for battery storage varies greatly, depending on the scenario assumed [42]. The numbers vary from 16.3 TWh up to 147 TWh for a 100% RES scenario [43–45]. Furthermore, Hartmann (2013) calculates the demand for storage as 6.3 TWh in a scenario with 80% renewables [43].

The improved utilization structure of the self-generated electrical energy created by the battery storage is not the only advantage that arises for the prosumers. In addition, there is the possibility to contribute to a smart grid [46] and to further curb CO_2 emissions [27, 47].

This leads to an improved infrastructure that also enables micro-grids in the low voltage range [28], which can help to avoid blackouts and failures [48]. All these effects have a positive impact not only on the environment but also on the economy and society.

1.3 Research Model and Associated Research Questions

As outlined in the previous chapter, there are various factors that are influencing and constraining the energy transition in Germany. However, some factors that are arising during the transformation of the energy system can be singled out in particular. The decentralization of electricity generation and the economic success of these decentralized plants are certainly two key points. Decentralization results from the technical requirements of the plants. The economic success of these plants must be guaranteed from the operator's point of view. These and other factors lead to new market models that do not follow the logic of large power plants. In addition, these new market models are driven by other factors from the ecological and socio-economic spheres. For example, one goal of the BRIDGE H2020 working groups in the European agenda is to position the customer further towards the center of the energy supply [49].

This situation leads to the overarching research question of this dissertation:

Overall Research Question:

How are economic, environmental, societal, and technological factors affecting the German energy transition towards decentralization and new market models?

To this end, the layers that influence new business models in the energy sector have first been identified. Since the energy sector is characterized by many different requirements and regulations, framework and regulations constitute the top level to be examined (see Figure 3). This is also due to the basically oligopolistic or even monopolistic structure that prevails in the energy supply sector in general. For the transmission and distribution grids, most of these structures are monopolies; for suppliers of electrical energy to private households, there is a larger market environment, but contracts are usually long-term.

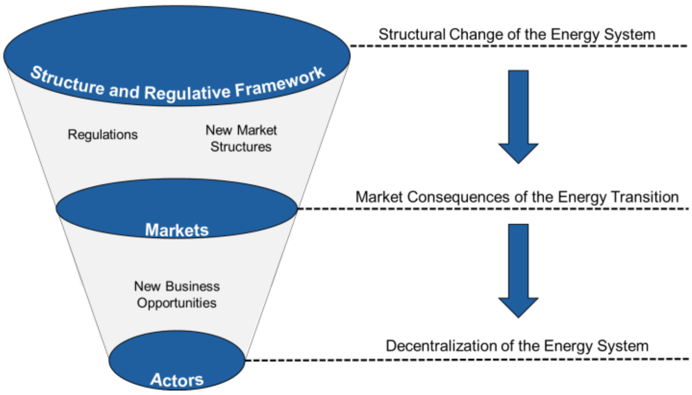

Figure 3: Layers identified for the energy sector's environment

In parts, therefore, there is already some liberalization for the end customer, but liberalization is greater for trade between generators and retailers. Here, there are basically three different layers in the market [50]. In OTC trading, long-term contracts are concluded for fixed delivery volumes at fixed times. Here, volatile generators are generally at a disadvantage compared with large fossil-fuel power plants. On the SPOT market, electricity is traded as on the stock exchange. Supply and demand determine the prices according to the merit order principle. The relevant markets here are the day-ahead market and the intraday market. On the day-ahead market energy can be bought for the following day, which is forecast to be sold. The intraday market can refine this in a certain time window.

Nevertheless, there can never be an exact match between the purchased quantity and the quantity actually requested. The balancing energy market exists to address this discrepancy. It serves to maintain stability for the frequency and the voltage in

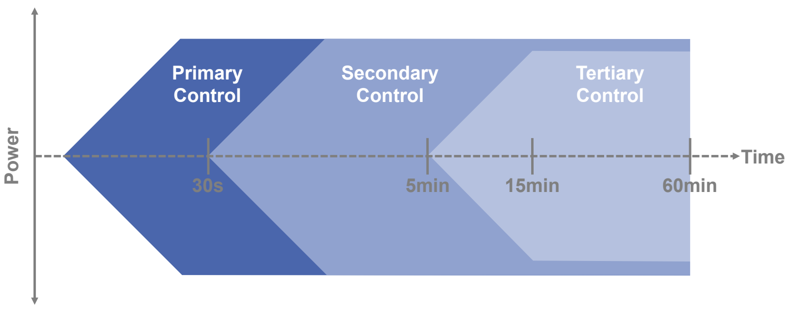

Figure 4: The three services in the balancing market [51, 52]

the network. Here, a distinction is made between three areas: primary control, secondary control and tertiary control. These three areas are differentiated according to reaction speed and length of energy available at short notice [51, 52]. In addition to the energy actually provided, the potential operational capability of the plant is also remunerated. The prices for both services are also determined in a bidding process.

In addition to these three market areas – OTC, SPOT and balancing market – there are further regulatory requirements. For example, small PV systems with a nominal output of less than 10 kWp can feed into the grid at a fixed tariff [39]. This means that they do not have to participate in any market, which is intended to lower the hurdle to installing a private PV system and to increase the amount of decentralized PV systems [53] and is depicted at the lowest layer of the "Actors" model (see Figure 3). New, small players are thus enabled to participate in the energy transition without having to participate in a market system.

This dissertation focuses its analysis on the economic viability of the different options that arise. Revenues generated from subsidies or through market participation, i.e., the economic success of decentralized solutions, are a key issue influencing the success of the energy transition [53]. The approach of economic efficiency is complemented by the influences and consequences on the ecological and social side and the technical feasibility.

This dissertation is divided into four research papers, which are structured in such a way that the first of these examines the structural and regulatory framework. The focus is on the question of how the energy transition came about in Germany. In other words, what events and factors led to the energy turnaround being initiated and driven forward (see Figure 5).

The results of this study have led to the conclusion that it can make sense to involve as many end customers as possible in an energy turnaround. This is also in line with the customer-centric energy model presented by the BRIDGE working groups [49].

In this way, the prosumer emerges as a new actor who is an energy-producing end customer. The prosumer becomes the focus of the second and third research papers. In these papers, the economic viability of the prosumer model from the operator's point of view, and thus its enforceability under German market conditions, is examined.

Based on these results, the fourth paper takes a look at the market level. The goal is not only to ensure a more balanced distribution of the generated energy among the participants of the energy community by combining a large number of prosumers, but also to generate revenues as a market participant in the day-ahead market and the balancing energy market. This pursues a further goal of not having to continue to rely on state subsidies but still being able to operate profitably.

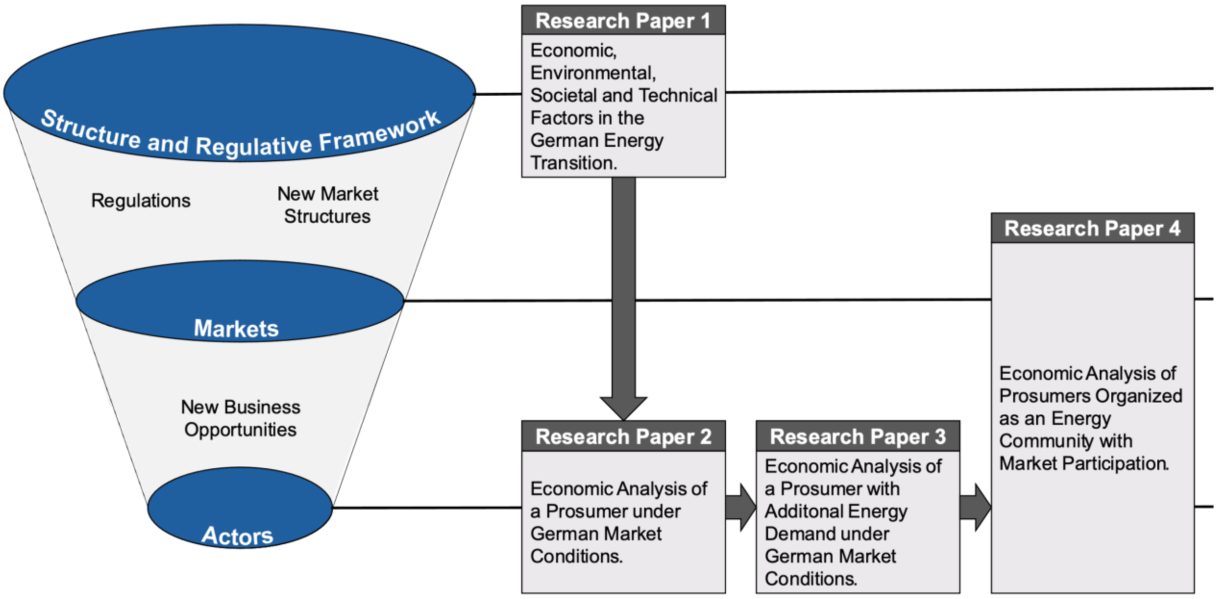

Figure 5: Structural change of the German energy system

In the first research paper, the structural and regulatory framework of the German energy sector is analysed, while in the second and third research papers, the transformation of the energy sector within a decentralized and customer-centric energy system is analysed. For this, not only the history of energy transition is analysed by its causes and effects in economic, environmental, societal and technical factors, but also different models of prosumer-based energy generation, storage and consumption are investigated by these factors. Research paper 4 integrates the market perspective into the decentralized model.

In research paper 1, different events of environmental, economic, societal and technical changes are analysed by their causes, effects and interdependences between these four pillars. In consequence the following research question is addressed.

Research Question of Research Paper 1

How can the events and effects in the course of the German energy transition be classified with a cause-and-effect analysis and which interactions between the events and effects can be identified?

The results show that Germany's energy transition is not a result of the causes and effects from one pillar only. It is more the case that the interactions between the factors from all four pillars have enabled the energy transition. However, the energy transition was introduced by and continues to be supported by society. In consequence two main outcomes can be observed.

First, companies which retain an inflexible business model suffer from potential disadvantages. Second, the energy transition positions society, and therefore the customer, at the centre of action.

Hence, in research paper 2 the prosumer is analysed as a new and disruptive market player. In a comprehensive prosumer-focused total cost of ownership analysis (TCO_P), different scenarios of production, storage and self-consumption are investigated to answer the following research questions.

First 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?*
Second 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?*

The investigations show that under current market conditions the prosumer model can only add financial benefit by operating a PV system without storage capacity. Thereby, the simulation also respects subsidies given to private prosumers.

Furthermore, the third paper adds additional energy demand for heating and hot water supply to the prosumer's household. Different heating systems, such as a heat pump or a gas heating system, are also added to the private prosumer to investigate whether sector coupling can increase the financial benefit. The research paper respects the additional electricity demand if the latter is requested. Other studies have shown that demand-side management can support the integration of renewable generation [54, 55], which requires interfaces between the generating, storing and demand units and smart solutions for managing these units within the domestic household. For the investigation of the research paper 3, the following research questions are answered.

First Research Question of Research Paper 3: *Can the use of battery energy storage (BES) become financially advantageous for a private prosumer when considering all energy needs of a domestic household?*
Second Research Question of Research Paper 3: *What improvements in self-sufficiency can be achieved by the technical configurations of a prosumer?*

The results of research paper 3 underline the lack of financial benefit when operating a storage system privately. Even with additional demand and demand-side management, the battery storage system does not pay off, although self-sufficiency can be increased.

As Figure 5 shows, the market layer is introduced as a mid-layer between the structural and regulatory framework and the actors. In Germany, this layer has already been established by the implementation of the electricity stock exchange. However, this market layer is currently not considered for small and medium power generation and storage. Therefore, in research paper 4 the market layer is considered for prosumers who have been organized into energy communities to empower them to participate in the market systems. Market schemes can mediate between legislators and actors, since, in this case, actors are more agile and create added value to the infrastructure by offering additional load or energy. Figure 6 shows the context of the added market layer. It can be seen that the layers of markets separate opportunities between the top and the bottom of the value chain.

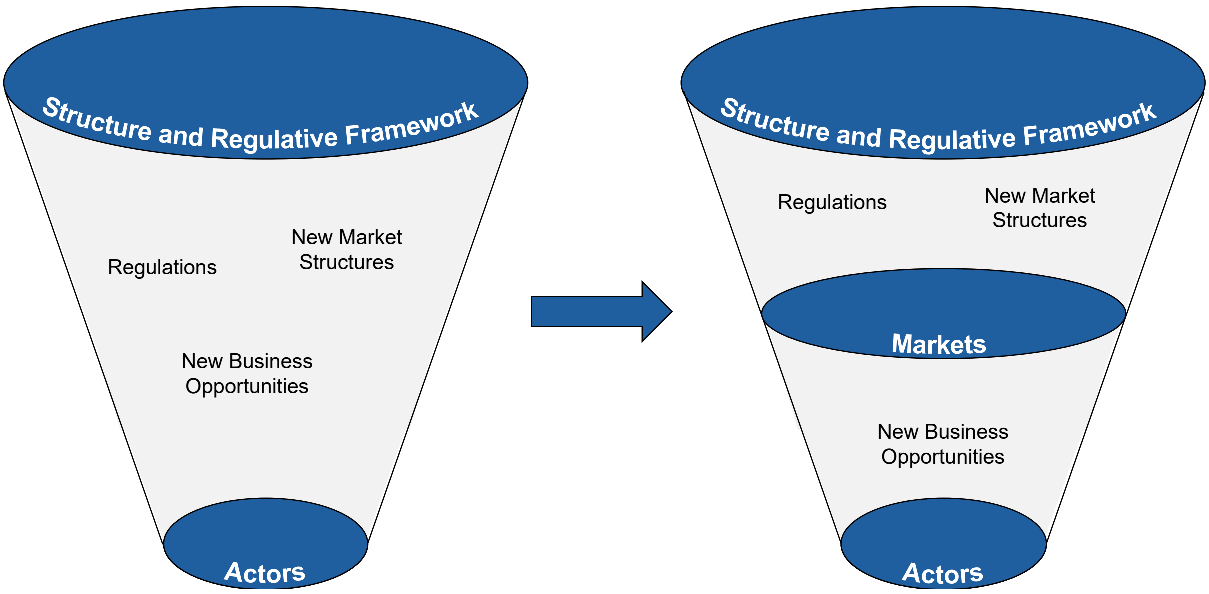

Figure 6: Overview of the market model layers

In research paper 4 the business model of an energy community is analysed by its created financial value. Therefore, the energy community participates not only in the day-ahead market, but also in the secondary and tertiary balancing market. The research question to be answered in research paper 4 is as follows:

Research Question of Research Paper 4

Does it pay off financially to run an energy community which operates on the Balancing Market under German market conditions?

The results show that energy communities can be operated with financial benefit even with 100% PV-based generation. Furthermore, decentralized storage opportunities can create an added value.

In the following section, the model is defined. Furthermore, the current state of research is presented and explained in order to evaluate the different papers and their results.

2 Definition of Model Concepts and Current State of Research

First, the structural changes of the energy generation and electricity deployment are described. This includes the factors of the pillars of economy, environment, society and politics, and technology. Second, the market consequences caused by these changes are classified. In the third sub-chapter, the effects of decentralization and affected actors within a decentralized electricity system are analyzed.

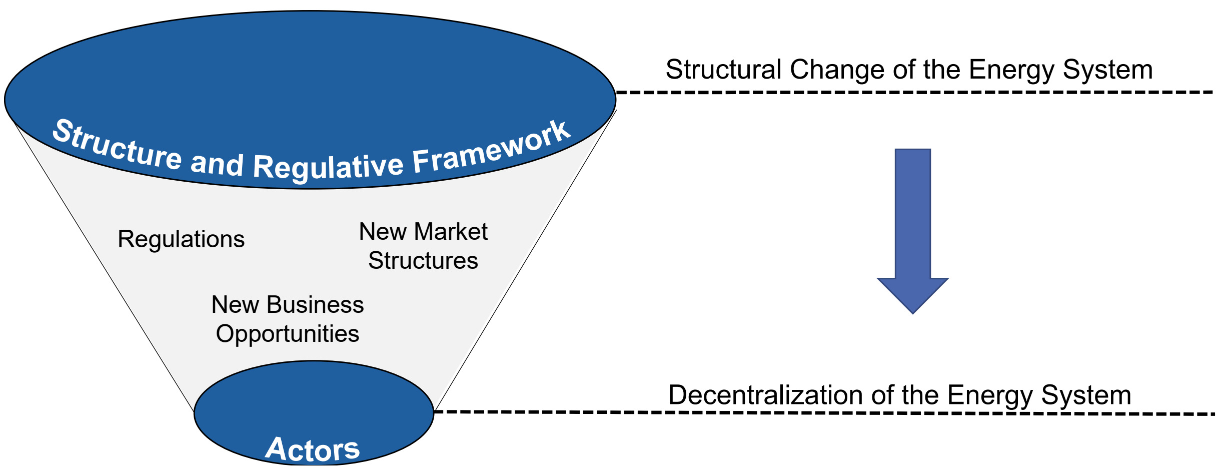

Figure 7: Preliminary model of the German energy transition

The explanation follows the already introduced diagram of the layers in the model of the energy transition, as described in Figure 7. First, it can be deduced from the regulatory requirements that new players will enter the energy sector or that existing players will undergo a transformation. This results primarily from the structural change in the energy system towards decentralization [27]. New players, such as prosumers, are coming into the focus in this context. In research paper 1 the structural change of the energy system is analyzed, while research papers 2 and 3 investigate the decentralization of the energy generation and especially the prosumer as one actor in the energy transition. In doing so, the research papers first consider the structural and regulatory framework of the energy transition in Germany and the changes that are arising for the actors. The findings of the first three research papers suggest that the middle layer of the market scheme needs to be considered as well to gain a comprehensive evaluation of the impacts that the energy transition has on the different layers. Figure 8 visualizes how the market layer fits into the model and how the structural change of the energy system, the market consequences of the energy transition, and rising actors are connected to each other.

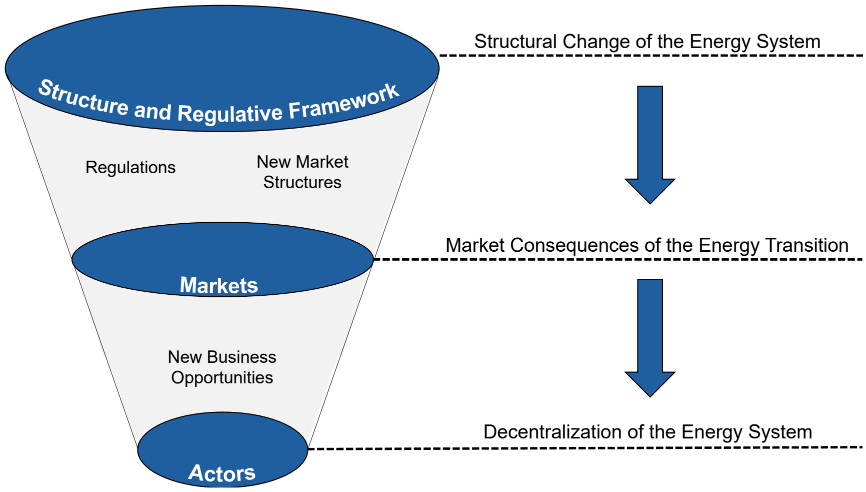

Figure 8: Layers identified for the energy sector's environment

2.1 Structural Change of the Energy System

The structural change of the energy system is a change that is happening on many layers and involves several factors. Grübler et al. (2002) emphasise that an energy transition is a technological change introduced by politics [56].

The structural change of the energy system from society's perspective is reflected in several non-governmental actions, such as #FridaysForFuture. In Germany, movements against the use of nuclear power also led to the founding of the political Greens party, which has been repeatedly elected into the *Bundestag* national parliament over the last three decades [57].

The societal and political support for the energy transition has been triggered and accelerated by occurrences of environmental catastrophes. Incidents such as the oil crisis, the Chernobyl accident or the Fukushima accident have led to political decisions which support the energy transition in Germany, as research paper 1 describes.

From a technical perspective, renewable energy generation also means smaller generation units on a decentralized level [27]. While conventional power plants use the economies of scale on the production side, renewable generation is organized into small units owing to the use of solar radiation or wind. This leads to new opportunities for electricity generation. For instance, electricity can be generated closer to where there is demand for it, which affects the grid structure and the grid management. Furthermore, renewable energy sources are much more volatile regarding availability. This volatility necessitates a large storage infrastructure with additional adjustments to the regulatory framework [58].

These opportunities and restrictions contribute to the structural change from an economic perspective. As the share of renewable energies increases, the power supply system will become more complex and thus more technically and economically costly [59]. On the one hand, investments in generation, storage and distribution infrastructure have to be made and, furthermore, market participation for small units has to be ensured. On the other hand, existing and obsolete infrastructures have to be rebuilt or adapted to the new use cases. The different factors are coming together in political efforts [60]. Driven by society, a new regulatory framework as well as incentive schemes has already been made and must be continuously adapted. European politics support distributed generation [61], and the German Network Development Plan [62] leads to higher efficiency of the grid. Studies imply that bottlenecks in the grid could also occur in the same geographical regions in the future as in those where they already exist today [63]. However, the German energy transition will transform the country's energy generation and distribution infrastructures towards more complex and small-scale levels. Current research is elaborating ways to adopt renewable generation, for example for privately owned generation units, by creating new business models or an adequate market model [27, 64, 65].

However, the general and the structural change in the energy system affect the generation as well as the grid infrastructures. With growing feed-in at all voltage levels, there will be increased fluctuation in load flows. Together with greater volatility of loads, this will lead to fundamental changes [66]. Due to new technical opportunities, large power plants can be complemented by small-scale generation units. Conventional power generation plants, such as coal-fired power plants, will continue to reduce their contribution to the base load [67]. This will lead to grid control systems having other needs if they are to guarantee a stable energy supply. However, prosumers are being positioned at the centre of the energy transition. On the one hand, this is leading to rising market structures for hardware, such as home storage solutions [68], or for the electricity market itself, which is supporting the energy transition. On the other hand, current regulations can be barriers to the implementation of renewable generation, and the balance between large-scale generation and local solutions is yet to be found. These situations challenge Germany's energy transition [61, 69].

Therefore, in the following sections, the move towards decentralization and the prosumer as a rising actor in the energy transition, as well as the market consequences of the energy transition, are summarized.

2.2 Decentralization and Prosumers

Technical developments are affecting Germany's energy transition, as already described. Renewable generation units are smaller and more decentralized than conventional power plants. In Germany, the share of renewably generated consumed electricity increased from 6% in 2000 to 36% in 2017 and to 56% in 2023 [70]**.** Furthermore 59 GWp PV capacity was installed in 2021 [41] which is the second largest share of generation systems in Germany [38]. On the one hand, this leads, due to the high volatility of PV systems, to a rising need for redispatch measures, which increased from 4,956 GWh in 2012 to 21,546 GWh in 2021 [71, 72]. On the other hand, the system cost per newly installed kWp in PV decreased about 75% from 2006 to 2020 [73]. The necessary redispatch measures are an indicator for the challenges that the grid faces with a rising share of highly volatile generation, but also the opportunities to not only generate electricity geographically where it is needed, and in terms of load management [74]. By reducing transmission and distribution losses [75] decentralized electricity generation does not only have an economic impact but also an ecological one. Moreover, the security of the energy supply increases with decentralized generation units [61], while the number of incidents in terms of fatalities decrease [76], which means that decentralized energy generation achieves social benefits [26]. The developments in these three areas, economic, environmental, and societal, are supported by adequate plans for storage and consumption [77]. Such consumption schemes can also help to reduce CO_2 [27, 47], since electricity does not need to be taken from the public grid; it can be used when available from renewable local generation units, thus supporting the transition towards smart energy consumption [46].

A rising actor in the energy transition is the prosumer. A prosumer is an economically motivated customer who produces electricity for self-consumption but who also distributes it to the grid [68, 78]. To be able to fulfil these attributes, the prosumer needs components such as a generation unit, an electricity grid, and storage opportunities [78]. Particularly the use of storage systems, such as batteries, increases self-consumption [79]. Furthermore additional active management systems for energy management or electric vehicle charging can be part of the prosumer's infrastructure [68]. Figure 9 visualizes a schematic representation of a private prosumer including elements of the concept of sector coupling as described in research paper 3.

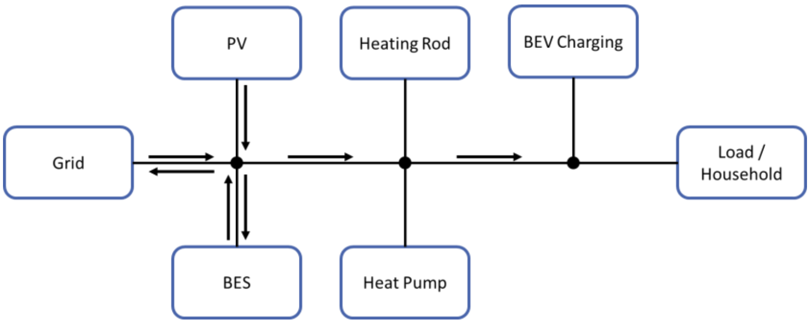

Figure 9: Schematic representation of a private prosumer (based on research paper 3 and Kappner (2023) [1]*)*

Smart units, such as energy management systems, support prosumers in achieving their goals in terms of self-consumption or distribution of electricity [78], although for households no deterministic way has yet been found to predict the volume of self-consumption [80]. As mentioned earlier, storage options are the best option to increase self-sufficiency and to manage the energy flow. But analyses indicate that the investment costs for batteries are still too high to be financially beneficial in supporting prosumers with storing electricity (see research papers 2 and 3, and [28]). In consequence, this leads to a highly volatile electricity supply in the low voltage grid, which causes risks [68].

Table 2 provides an overview of the primarily business research on the prosumer.

#	References	Business Adminis-tration		Economic	Technical	PV	BES	Description
		other	TCO					
1	Akter, Mahmud, and Oo 2017 [81]	X				X	X	• solar photovoltaic units and battery energy storage systems • levelized cost of energy along with reduction in carbon di-oxide emissions and grid independency • in Australia
2	Bertolini, D'Alpaos, and Moretto 2016 [82]	X	X			X		• impact of a PV system for micro grids
3	Bortolini, Gamberi, and Graziani 2014 [74]	X				X	X	• Economic model for grid connected PV and BES system • In Italy
4	Comello and Reichelstein 2017 [83]	X				X		• Economic efficiency of PV in the U.S. • Remuneration system
5	Cucchiella, D'Adamo, and Gastaldi 2016 [79]	X				X	X	• profitability of PV systems • profitability of energy storage in a mature market • in Italy
6	Kamankesh and Agelidis 2017 [84]	X		X		X		• Optimising the management of the grid with high share of RES and vehicle to grid
7	Kaschub, Jochem, and Fichtner 2016 [85]	X				X	X	• developments of battery storage technology with PV • generation mix of utilities, distribution grid utilization, and electricity price
8	Klise, Johnson, and Adomatis 2013 [86]	X	X			X		• TCO for PV systems in the U.S. • Incl. discounted Cash Flow
9	McDowal 2017 [87]				X	X	X	• Meaning of BES for the autarchy of micro grids
10	Naumann et al. 2015 [88]	X			X		X	• Costs and revenues for BES • Techno-economic model for revenues
11	Rosen and Madlener 2016 [89]			X				• Changes in market regulations • Enable trading of energy for prosumers
12	Rylatt et al. 2013 [90]			X	X			• Market model • Prosumer is embedded in an aggregator structure
13	Uddin et al. 2017[91]	X				X	X	• photovoltaic systems integrated with lithium-ion BES • in UK
14	Vosoogh et al. 2014 [92]	X		X	X	X	X	• Optimising the energy flow in a micro grid
15	Zhang et al. 2016 [93]	X				X	X	• three different types of BES • in Sweden

Table 2: Overview of the literature on prosumers (analogous to research paper 2 [4] *and Kappner (2023)* [1]*)*

The table above shows that there are already various studies on PV and BES in financial terms in existing literature. Some of these focus exclusively on the consideration of PV [82, 83, 86]. Others focus on markets in Austria [81], Italy [74, 79], Sweden [93] or United Kingdom [91]. There are also studies that are limited exclusively to the evaluation of one household size [85]. Most work with linearized prices for assets or services, which only reflects the conditions of a prosumer to a limited extend. There are also investigations on how the prosumer model can be expanded (see also research paper 2 [4] and Kappner (2023) [1]).

Community-based solutions, which can be built as micro-grids for the interaction of prosumers [68], can minimize risks and generate benefits for both the grid and the prosumers [94]. Prosumers are key in the creation of smart grid and community-based solutions for energy generation and consumption [95]. A combination of energy sources and presumably decreasing costs for PV systems and battery storage systems will increase the level of self-consumption [96] and therefore minimize the transmission and distribution losses. Even if the best deployment level for batteries still has to be found [29], it can be stated that the coupling of resources will increase the efficiency of electricity generation and can bridge the gap between consumption and production [97, 98]. Decentralized community-based solutions can be part of local electricity markets and can implement mechanisms for managing local electricity generation and demand [99]. Figure 10 visualizes a schematic representation of a decentralized community-based union of prosumers which can be called energy community.

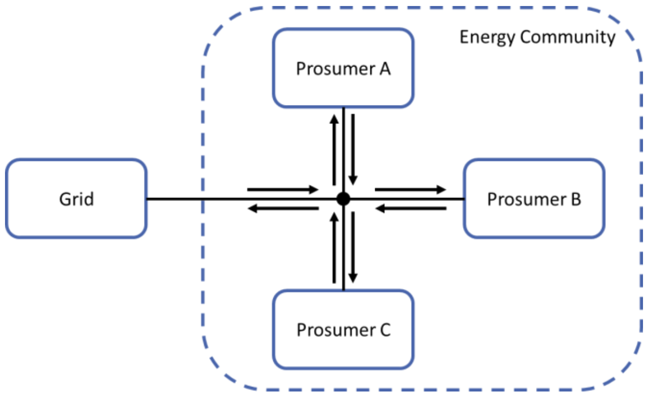

Figure 10: Schematic representation of an energy community

The changes in decentralization and the additional actors in the energy sector have an impact on the energy market system, as described in the following section.

2.3 Market Consequences of the Energy Transition

The market consequences can be summarized in four areas where the most obvious changes are taking place from a technical perspective (see Figure 11). Large energy-generation plants will be replaced by many small units. These will be distributed in a decentralized manner over the geographical area. The integration of these smaller and decentralized systems will move the distribution structure of the power grid from a top-down structure towards a mixture of a top-down and a bottom-up structure. Distribution grids will thus play an important role in the success of Germany's energy transition [100]. In addition, renewable generators are more volatile due to their dependence on solar radiation and wind.

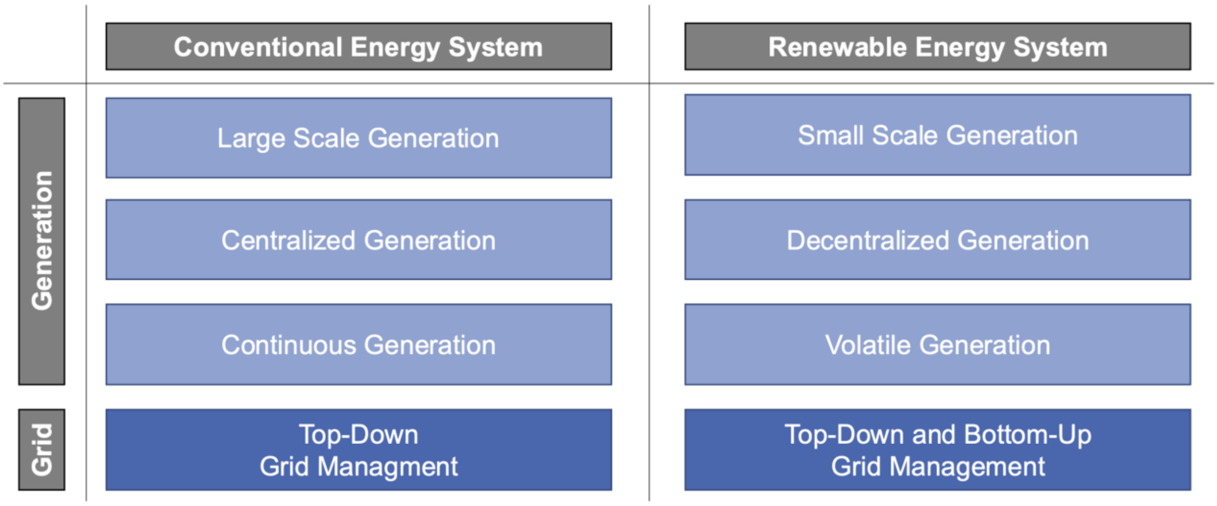

Figure 11: Areas of change within energy transition

In the future, the energy system will face challenges with consequences for some of these areas. These need to be covered by the market system. Market mechanisms and business models can help to make innovations more effective, especially if the innovations are systemic ones, such as the energy transition [101]. Thereby, two important principles support the energy transition. First, the value of resource flexibility has to become more visible in the market prices. Second, resource flexibility has to decrease in general. Furthermore, demand-side resources have to be considered as very important [102]. Under these circumstances, domestic households can play an important role in the transformation of the energy system by transforming from consumers into prosumers [27]. This will not only have a microeconomic effect on the prosumers. Also, macroeconomic effects are measurable, such as the investments in power generating technologies and the higher income of prosumer households, which will lead to higher consumption and will stimulate economic growth [27]. Depending on the type of system, a PV generation system with a size of 10 kWp enables a self-sufficiency rate of between 20 and 70% for one household [103]. This makes also clear that the market dynamics are changing. At peak times, generation systems produce more energy than demanded and there are also times in which even prosumers demand energy from the grid. Additionally, to these seasonal effects, a high volatility of the generation itself can be observed. This is reflected in the markets, since the volume of the intraday market increased over the last years, while the volume of the day-ahead market was staying during the same period [72, 104]. To buffer the volatility locally, batteries can contribute to the energy transition by lowering peaks in generation and demand

and enforcing self-consumption, which would change the energy system radically [96]. In fact, the distribution systems will switch from having a passive role to being an active network which controls distribution and power flows bi-directionally [105]. Based on the possibility of storing electricity and managing energy flows actively, new market schemes and business models are arising which will make energy generation and distribution more efficient and decentralized. These new models must ensure a well-balanced mixture of increasing energy efficiency and cost effectiveness [106]. For the successful creation of sustainable innovations, not only the value proposition to customers is affected but also how the company involves suppliers and acquires resources profitably [107]. In Germany, the energy distribution is currently based on a top-down mechanism. The system is shifting towards prosumers, and decentralization will change current mechanisms into a mixture of top-down and bottom-up effects [30, 59, 66], which is also shown in Figure 12.

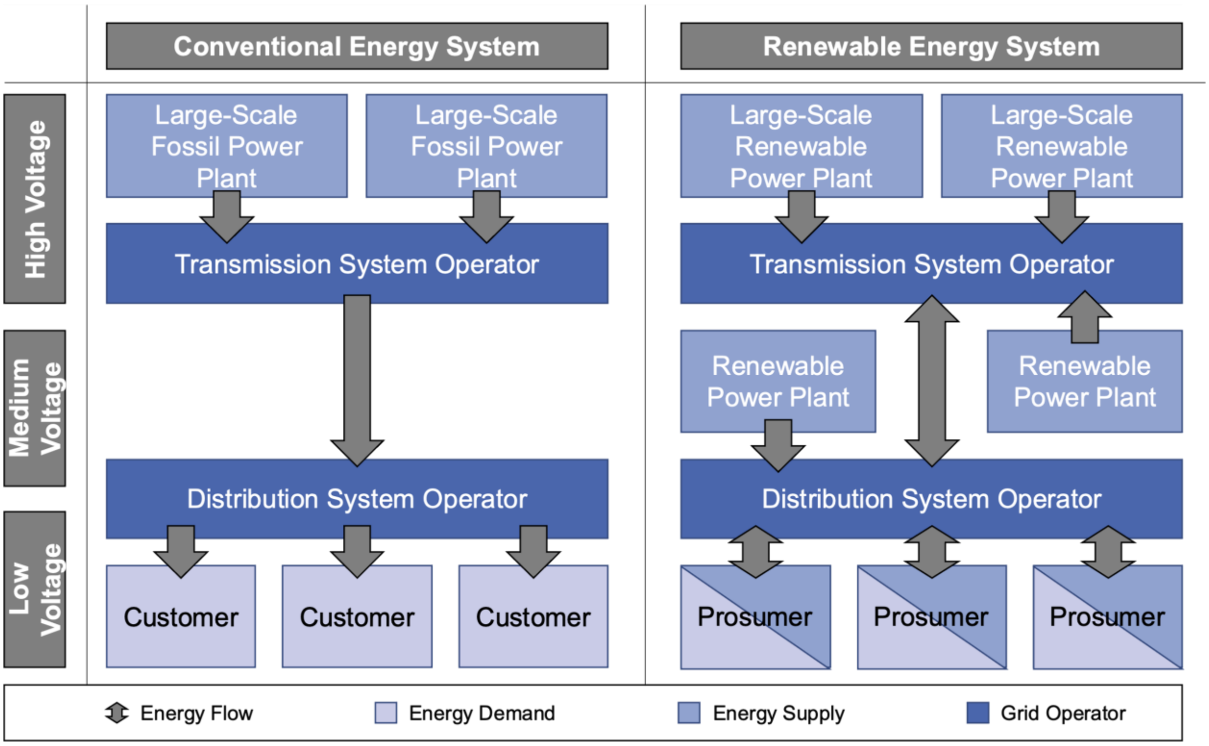

Figure 12: Current and future market models (based on research paper 2 [4]*, Schleicher-Tappeser (2012)* [108] *and Kappner (2023)* [1]*)*

In reaction to the changes in the energy transition, energy markets will become more volatile and will not only react to price signals. Bundles of prosumers – so called energy communities – can offer chargeable services to system operators or other consumers [68]. Furthermore, micro-grids can create their own local markets and autonomously exchange energy from prosumer to prosumer [47]. Both ideas will be expressed in the next section.

In summary, it can be stated that the German energy transition is having a major impact on the energy system at various levels. On the technical side, generation systems are becoming smaller and more decentralized, which not only opens up new opportunities for end customers, but also poses risks, as the distribution grid in particular has to withstand additional loads as a result. These technical aspects also have an impact, not only on the environment but also on social and economic aspects. In social terms, the end customers are thus brought into focus. The installation of small systems gives them the opportunity to participate in the energy market. On the economic level, the energy market, as a result of the changes, is the focus of attention. Due to decentralization, volatile generation and the influence of political rules, the liberalization of the market but also subsidies are important components that can contribute to the success of the energy transition in Germany. These schemes are examined in this dissertation and, among other things, the economic efficiency of the prosumer is taken as the object of consideration. In the following, the methodical procedure will be described.

3 Research Methodology

As can be seen in Figure 13, this dissertation is based on two methodologies: first, a Cause and Effect Analysis (research paper 1) and, second, Simulation Modelling (research papers 2, 3 and 4). The methodologies are used to identify the main factors influencing the energy transition and its actors (research paper 1) and, thus, to analyze the impact of costs, the regulatory framework, and the markets.

The use of a simulation model with integrated total cost of ownership analysis is particularly suited to the complexity of the research questions. The different requirements of the analyzed objects of observation can be considered purposefully and flexibly by a simulation model. For example, changing environmental conditions in the models are included and adapted for the different research questions. A rich database, with real market data, consumption data and generation data, underlies the analyses.

The next sub-chapters introduce the approach for the Cause and Effect Analysis and also the simulation models used for the different research papers.

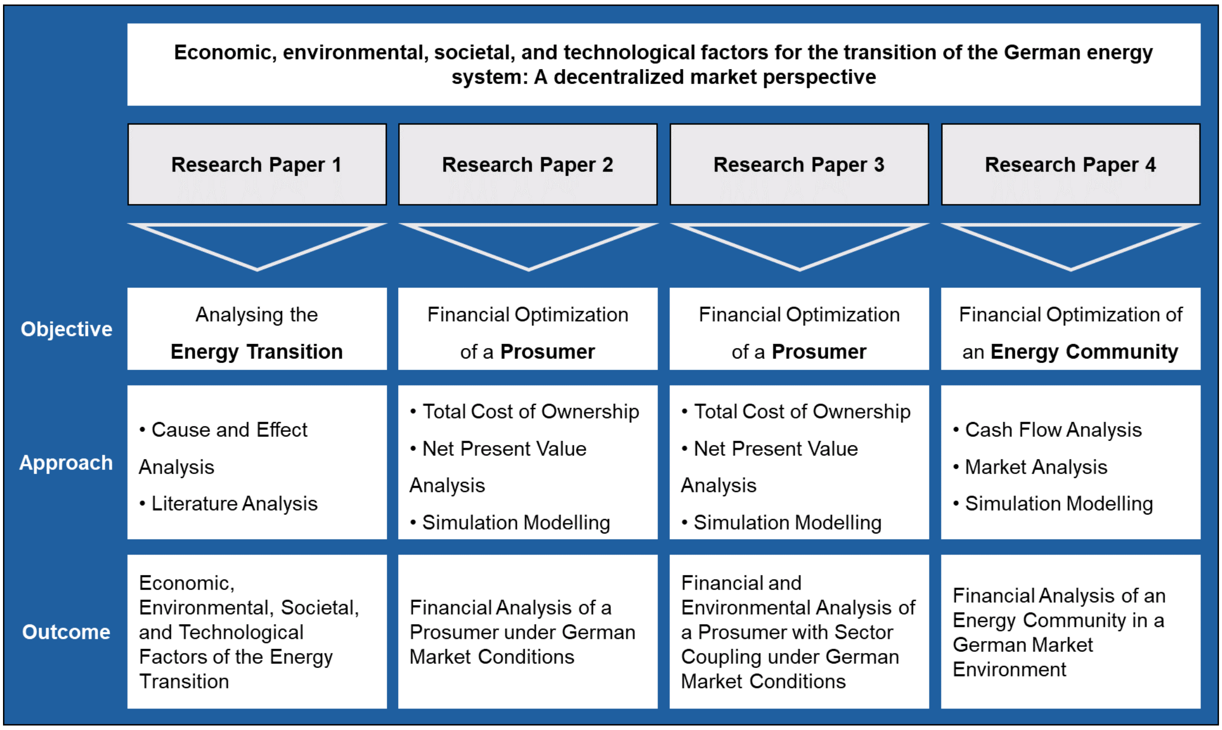

Figure 13: Objectives and research methodologies used in the four papers (based on Suares (2019) [2]*)*

3.1 The Cause and Effect Diagrams

Cause and Effect Analysis is used in research paper 1. The cause and effect diagram was created and developed as a tool for quality management by Kaoru Ishikawa, thus it is also called the Ishikawa diagram [109]. Because of its structure it is furthermore known as the fishbone diagram [110]. Since the cause and effect diagram originates from the area of quality management, its structure helps to organize the different perspectives of a problem or a question. The structure further enables a clear view of complex issues and presents the search for and development of causes [109, 111]. Due to the advantages of Cause and Effect Analysis, this method has also been introduced into other disciplines, such as the field of business administration, where it is used to investigate the causes and effects of business processes. It has also been used in various research projects. These are just some of the various possibilities offered by Cause and Effect Analysis [111–114].

In this dissertation, Cause and Effect Analysis is used to identify the impact of events and actions on the initiation of Germany’s energy transition. The analysis is conducted by investigating the three pillars of sustainability, i.e., the economy, the environment, and society and politics. These pillars – or perspectives – are supplemented here by a fourth perspective of technology. To analyse the development of the energy transition in Germany, the impact factors are allocated to the relevant perspectives. Furthermore, the interactions of the impact factors are analysed by bringing them into the context of a timeline to show which events have supported the energy transition the most. The cause and effect diagram shows the various factors which have had an impact on the analysed question and can also express interdependencies between the factors. This makes the cause and effect diagram an adequate tool to analyse the different impact factors of Germany's energy transition.

3.2 Simulation and Modelling Approach

The simulation and modelling approach is used in research papers 2, 3, and 4. While the models in research papers 2 and 3 simulate the individual prosumer, the outcomes of these papers 2 and 3 are used to model an energy community in research paper 4. This particular approach has been chosen to analyse a real-world problem under real-world conditions as closely as possible. The simulation allows the usage of real-world data, such as consumption, generation and market data, to model scenarios. The setting of realistic boundary conditions is crucial to obtain meaningful results. These boundary conditions can be set either by taking into account the currently valid regulation model or to proof the validity of other regulations and the market models which are investigated. Physical boundaries, such as charging capacities or generation limits, need to be respected in the simulation model as well.

The simulation models in research papers 2 and 3 are built analogously. The models simulate energy generation, consumption, and storage. The energy flows are cost-covered. Furthermore, the investment costs of the assets and the operational costs of the systems are considered and a lifespan is given to calculate them. This total cost of ownership (TCO) approach helps to identify all the relevant costs involved [115] and to understand the true costs of buying and running a certain asset or service [116]. Hence, all relevant costs throughout the value chain are considered in the TCO analysis [117] by understanding, analysing, managing and reducing the total cost of ownership of used assets [118]. The TCO is based on the listing of cost drivers during the life cycle and allows an evaluation of the financial added value during the utilization phase. Thus, the TCO includes a broad scope of cost-affecting perspectives [116, 117, 119, 120], which makes it advantageous in comparison to other comparable approaches [121]. The model assumes that decision makers, in this case prosumers, need to have a transparent overview of all the costs in conjunction with the investment project, such as transaction costs and end-of-life costs [116, 119]. It also assumes, that the decision does not affect any other financial stream besides the analysed one [115].

Since the cost analysis of the models in research papers 2 and 3 is long-term oriented, further financial effects occur [122]. This is, why the TCO is used together with the annuity-based calculation of an investment's net present value (NPV) as follows:

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

The prosumer-based total cost of ownership (TCO_P) is bringing together all prosumer-related cash flows into a long-term perspective, while C_{NPV} is the net present value, t is the period under review and i reflects the discount rate for all payments. Furthermore, all costs are calculated per year.

Therefore, the net present value (C_{NPV}) is adding up all observed cash flows, which are discounted over t with i, as follows (see also research paper 2 [4] and Kappner (2023) [1]):

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

The capital expenditures (C_{apex}) represent the investment costs; the sum of the operational expenditure in period t ($C_{opex,t}$) represents the discounted cash flows over time. In the simulation model, the NPV is calculated with internal and external parameters, as described.

Research paper 4 also focuses on cash flows. Outcomes from research papers 2 and 3 are taken and supplemented by other data. For the simulation, market data from the SPOT market are used as well as the balancing markets for secondary and tertiary control. The SPOT market focuses in particular on the day-ahead market. With the given boundaries, an algorithm compares the financial advantageousness between storing the energy and offering it to the SPOT market or to one of the balancing markets. Alternatively, in the case of a given capacity, a comparison is made of the financial advantageousness between keeping the capacity and buying energy from the SPOT market or from one of the balancing markets. Based on the following formula of the NPV, the net cash flow (NCF) is determined:

$$NPV = \sum_{t=0}^{m} \frac{NCF_t}{(1+r)^t} \tag{3}$$

t represents years and r the discount rate. The main difference to the previous formula is the integration of the C_{apex} in the net cash flow. The model of the energy community calculates without self-owned assets but with compensation fees for providing the assets owned by the energy community's participants to the energy community.

The simulation model fits best to analyse the economic outcomes of new and rising business opportunities offered by the technical changes of small and decentralized generation units, since prosumers and energy communities can be simulated within the context of regulations and subsidies. To investigate the effects of changes in markets and subsidy schemes, the simulation model is accordingly adapted to show the resulting consequences for the objects under consideration. A realistic investigation with real data is used for this simulation model. However, the investigation of an economically viable model is at the centre of the present analysis, following the idea that financial benefits for the actors in the energy system are supporting the energy transition.

4 Key Findings and Implications of the Different Research Papers

As already mentioned, this dissertation is composed of four research papers. Figure 14 shows the pillars of influence investigated in the first research paper, the resulting measures and objects of consideration and how they are addressed in the following research papers.

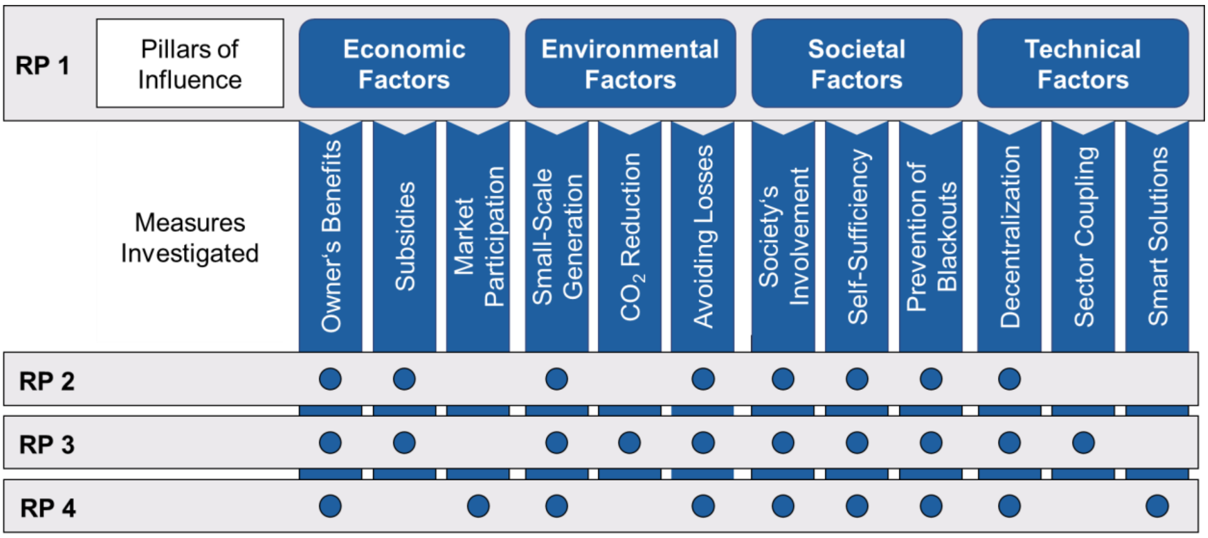

Figure 14: Influence factors found and investigated in the research papers

As can be seen, some factors investigated are studied in all four papers whereas others are only analysed in particular papers to underline outcomes or to show effects besides the economic results.

Therefore, the investigation shows that prosumers do not only have an economic effect but also a societal one. As additional infrastructure – mainly PV systems or battery storage opportunities – are investigated. Societal factors are self-sufficiency and participation but also the prevention of blackouts. Technical constraints include the discussion of decentralization.

However, some factors are only considered in selected research papers, such as subsidies, market participation, CO_2 reduction, sector coupling, and smart solutions.

4.1 Research Paper 1

The first research paper can be regarded as the basis for the further research conducted in this dissertation and has been published in Energy, Sustainability and Society (2023) 13: 28 [3]. To understand how the German energy transition was introduced and which effects have supported the transition, many events ranging from World War II until the Russian invasion of Ukraine in 2022 have been analysed in a Cause and Effect Analysis to investigate interdependencies between these events and to identify the main drivers of the German energy transition. Furthermore, the first research paper investigates the question of why the big German energy companies are struggling with the energy transition.

For the Cause and Effect Analysis an Ishikawa diagram is used. The factors of interest are allocated to the three pillars of sustainability (economy, environment, and society and politics) and complemented by a fourth, newly introduced pillar of technology. Firstly, the events of each pillar are investigated individually. Secondly, the interaction between the pillars is analysed. Within this analysis, different findings are obtained, and these can be summarized into two main outcomes. On the one hand, the German energy transition is being mainly driven by society and politics. On the other hand, the different pillars are closely interlinked, so that certain events may influence the further development of the transition. Furthermore, this research paper finds that technological improvements are always a result of demand. Therefore, it can be argued that waiting for a "technological leap" will not accelerate the energy transition, whereas political and societal requirements can promote it.

Besides these outcomes, the research paper reveals that the German energy transition has actually been ongoing for decades and political tendencies became visible a long time ago. Nevertheless, for the big energy companies in Germany, the transformation is challenging. One reason for that might be the large assets that the companies have, such as nuclear or lignite power plants, which have been politically supported since the end of World War II. However, it can also be concluded that these companies have underestimated the disruptive effect of renewable energy generators and the change in the energy system to support the energy transition. For instance, small and decentralized energy generation has been shifted increasingly into the focus of the country's energy system.

4.2 Research Paper 2

The second research paper investigates the model of a prosumer in the light of current economic conditions and policy. At the centre of the investigation is the financial performance within the German market framework and its specific characteristics and subsidies. The research paper has been published in Energy, Sustainability and Society (2019) 9: 44 [4].

The simulation model is used for one prosumer with the investment choice between different sizes of PV systems as well as different sizes of battery storage. For generation, real data from the area around the German city of Aachen are used. For demand, the H0 profile, which reflects the average demand of standard households, of the local distribution system operator (DSO) is used. The H0 profile represents the average electricity demand for domestic households every quarter-hour and is used in praxis to estimate future electricity demand. The simulation modelling focuses on the financial performance and takes subsidies into consideration. Nevertheless, the financial performance is based on the technical feasibility of the model, such as maximum storage capacity or the intensity of solar radiation for electricity generation.

The findings of research paper 2 are very clear from the financial perspective and they provide some guidelines for potential prosumers. First, a PV system always creates financial added value for the prosumer, independently of the size of the PV system, compared to the basis model, where electricity is demanded from the grid at average costs. Second, the larger the PV system, the better the financial added value. This applies up to the limit of 10 kWp, since this is the regulatory limit for receiving fixed subsidies. Third, battery storage creates no financial benefit for the prosumer in this setting, regardless of the size of the chosen battery storage system, compared to the scenarios with PV and no battery storage system but also compared to the basis model, where electricity is demanded from the grid.

As mentioned, the paper focuses on the financial performance of the prosumer. Nevertheless, the investigations indicate that the self-sufficiency rate, which shows how much self-generated energy is consumed by a prosumer, increases dramatically with added battery storage. It can be also seen that the self-sufficiency rate increases when a larger battery storage is provided. Although this result is clear, there is no financial added value in this study of a battery storage system for the prosumer, since the investment in such a battery system is still very high and the difference between the cost of electricity demanded from the grid and the fixed remuneration for electricity provided to the public grid is too low. However, it can be seen as the factor with the highest impact when calculating the cost-efficiency of the battery.

4.3 Research Paper 3

Similarly, to the second research paper, research paper 3 investigates the model of a prosumer for financial performance. Two extensions are made. On the one hand, the prosumer's demand is increased by sector coupling, while the energy needed for heating and hot water supply is taken into account. On the other hand, CO_2 emissions are calculated for several scenarios to evaluate the economic and the environmental benefit independently. The simulation models one prosumer within German market conditions, with investment choices such as those suggested in research paper 2 plus additional investment choices for heating and hot water supply, such as a heat pump, a heating rod or a gas heating system. While the gas heating system does not create additional demand for electricity, the other options are used for sector coupling and to investigate whether rising demand also has an impact on the financial performance of a prosumer, which would suggest decentralizing not only the electricity generation but also the generation of energy in general.

From a financial perspective, additional consumption does not necessarily achieve additional added value for prosumers under German market conditions. The studies have shown that the additional loads, for example by adding a heat pump, request energy especially when this does not increase the added value for the overall system. The heat pump, for example, is particularly needed in the winter. During this time, however, the stored electricity in the battery is at a very low level anyway, due to less sunshine during the day, so the addition of the extra load does not increase the utilization of the energy storage. However, the high investment costs of a heat pump or the high energy costs of a heating rod lead to even more financial disadvantages, although the additional load supports the amortisation of the battery storage system.

Finally, research paper 3 investigates the CO_2 emissions of the different scenarios. The emissions of the current electricity generation in average are considered for the emissions caused by the electricity demanded from the public grid. The simulation shows that a changing energy mix in a three-person household with a heat pump has a larger impact on the overall CO_2 emissions, by decreasing the amount of CO_2 emissions from 37.8 t/period to 30.2 t/period, than increasing the battery storage to increase the self-sufficiency, which leads to 31.6 t/period. The same effects can be seen in all the other scenarios, where consumption and heating options vary. In conclusion, it can be seen that higher effects can be achieved if the electricity mix in the public grid improves towards a higher share of renewable energy, than if the amount of decentralized storage capacity rises.

Nevertheless, additional, non-financial reasons can be considered by prosumers to raise their self-sufficiency by adding large storage capacities, such as the use of their own fully renewably generated electricity.

4.4 Research Paper 4

Research papers 2 and 3 show the challenges facing prosumers working by themselves by implementing the technical improvements, seen in chapter 2. This happens on the layer of "Actors" as can be seen in Figure 15. It becomes clear in research papers 2 and 3 that the prosumer as a single actor aggregates only small financial benefit. Therefore, this thesis argues to consider the generally existing market layer also for the decentralized generation, storage, and consumption done by prosumers, as visualized in Figure 16. In Germany, regulations and market rules are gradually being adapted in order to open up the market to renewable energy generation and storage options, as shown in research paper 4.

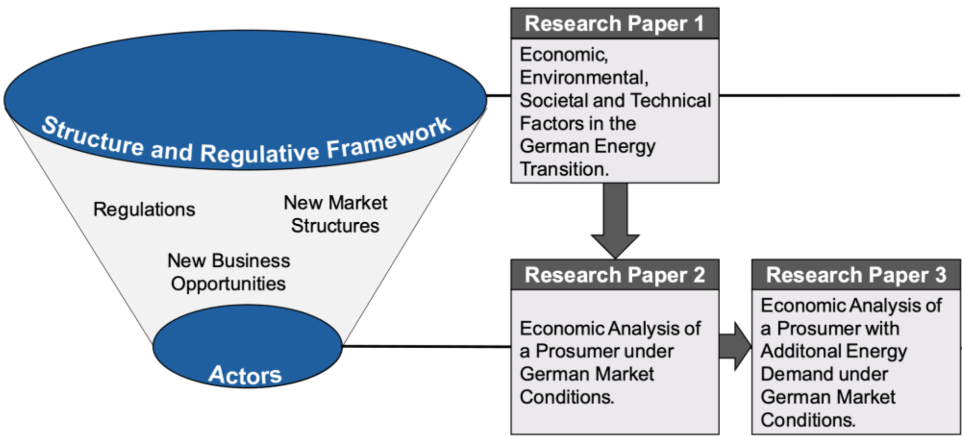

Figure 15: Interplay of the first three research papers

Research paper 4 reacts to this opening-up of the market and combines the prosumer, as a new actor in the energy transition, with new market schemes and business opportunities. The idea of an energy community-based network of several prosumers working together as one unit is financially evaluated in research paper 4. When doing so, day-ahead or the balancing markets participation is taken into account.

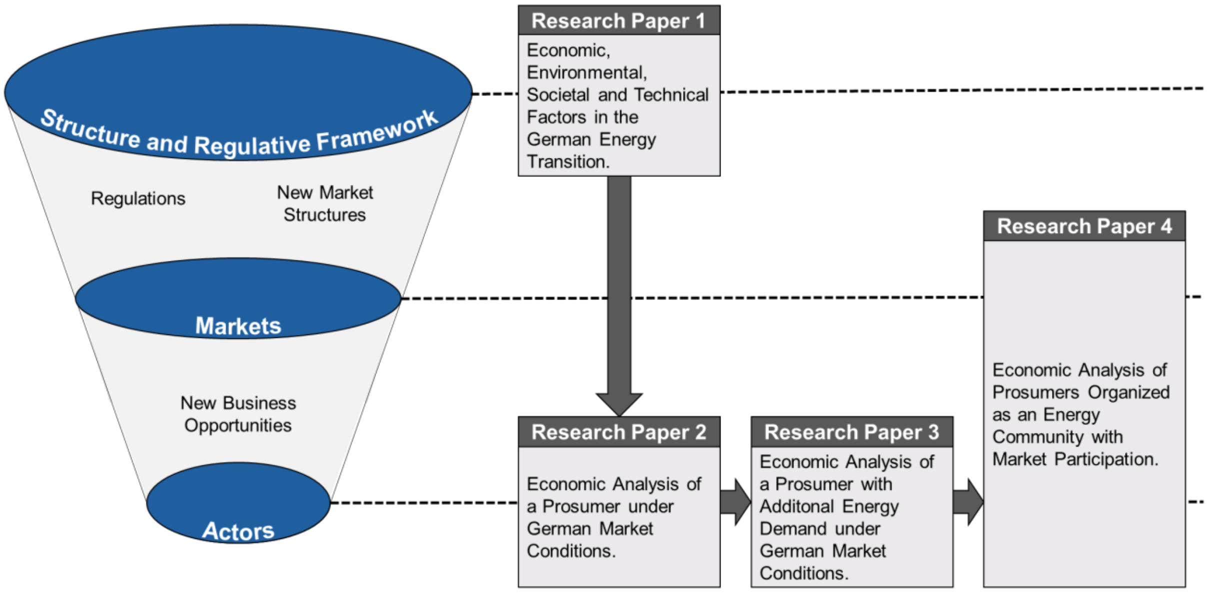

Figure 16: Structural change of the German energy system

The model simulates a certain number of prosumers, who, similarly to those in research papers 2 and 3, generate, store, and demand electricity. Although the object of consideration switches to the energy community, the needs of the individual prosumers are respected by compensating costs for assets such as PV systems or battery storage systems. Furthermore, an algorithm monitors the electricity generated, stored, and demanded by the energy community to analyse the financially most valuable decision for the energy community in terms of selling or buying energy from the SPOT or the balancing markets.

Furthermore, the simulation considers taxes, levies, and costs for participation in the energy market for the energy community in order to achieve the most realistic results for the simulation model, but also to identify regulatory leverages for making decentralized energy generation financially more attractive under market conditions. The options are analysed in different scenarios.

In general, the results show the financial benefit of the energy community in comparison to individual prosumers working by themselves. Furthermore, the results show that the effectivity of the energy community rises with a higher number of participating households, although the efficiency varies with the capacity, beginning with one megawatt, which allows participation in the energy markets.

Finally, all results of the simulation suggest the same conclusions, which can be expressed in three superior outcomes. These are formulated in research paper 4 as follows:

(1) The larger the energy community, the better the financial outcome of the energy community in total.
(2) Differently from what one would perhaps assume, VAT and grid costs for internally exchanged electricity within the energy community are not the main cost drivers. Hence, these costs do not constitute any barriers to promoting more energy communities.
(3) Battery storage is mandatory if energy communities are to operate with successful finances.

Furthermore, the results show that the absence of storage opportunities leads to no financial feasibility in any constellation, since the energy community is not able to participate in negative balancing markets or to store energy in order to participate properly on positive energy markets.

The simulation performed in research paper 4 confirms the economic benefit that energy communities can create for their participants but also for the energy system in general if the energy community participates in the balancing markets. Also, the results show that, for prosumers, being part of an energy community is financially more efficient than operating independently is. This result is likely to be reinforced when all subsidies are eliminated. This could have an enormous effect on the energy market but also on the electricity distribution itself.

5 Conclusion

In the following, a conclusion to this dissertation will be given. First, a summary shows the interactions of the structural changes towards decentralization and how the four research papers have investigated the economic impacts of this development. Second, the results of the four research papers are analysed and the interplay of the findings are classified as well as theoretical and practical implications are outlined. A third section describes the limits of the investigations and gives a preview of what topics could be at the centre of further research.

5.1 Summary

As chapter 2 shows, Germany's energy transition is bringing challenges with it caused by technical changes and the need for a new market system. As can be seen in Figure 16 the analysis is subdivided into three layers. First, the implementation of the energy transition is being driven by a new structural and a new regulatory framework with changes to regulations and market structures. This is leading to new market schemes with new business opportunities. The identification of central actors in the energy transition forms the bottom layer in this visualization.

Research paper 1 analyses the structure and development of the energy transition in Germany. The findings of the analysis show that society and politics set the framework for the different actors of the energy transition. Therefore, politics and society interact, while environmental factors trigger this interaction and the economy sets the starting position through already existing investments. Furthermore, research paper 1 indicates that technologies follow the progression of society and politics and the needs of the economy. Therefore, waiting for a technological leap will not accelerate the energy transition. The needed changes defined by society and politics create new opportunities for the economy in the three layers of regulation framework, market schemes and actors. Technologies are adding further opportunities, such as decentralized small-scale electricity generation, but also restrictions on these opportunities, such as volatile electricity generation due to the dependencies on solar radiation or wind.

The technological restrictions are considered in the second research paper, which is focussing on the prosumer. Following the idea of the need for financial incentives to provoke changes, research paper 2 investigates the financial added value of a prosumer in the German regulation system. It can be seen that producing electricity is, in the system of German subsidies, financially beneficial, but investment in storage systems is not within the given structure.

In research paper 3, additional electricity demand is added to the model to analyse the added value of battery storage and sector coupling for the prosumer. Again, the results imply that battery storage is still too expensive to gain financial profit for the prosumer, even with higher demand through sector coupling. Nevertheless, as a second result it could be shown that CO_2 emissions can be decreased dramatically in operation by using new technologies for energy demand, such as PV systems, battery storage, and heat pumps.

To combine the layers of markets and actors and to gain financial benefit for the actors, research paper 4 uses the merging of prosumers into an energy community. This energy community can participate in different energy markets and act as an electricity generation and storage unit in the public grid. Not only can energy communities help to stabilize the distribution grid, but an energy community can also create financially added value by participating in the energy markets. The simulation integrates the day-ahead market as well as the balancing markets for secondary and tertiary control.

Finally, this dissertation shows, that large structural changes, such as the German energy transition, need to be introduced via a structural and regulatory framework. Actors face different challenges: In case of established actors they experience the difficulties of changing business models, while in case of new actors, such as prosumers, they are confronted with the hurdles of high investment costs and market barriers. By respecting the third layer, the market, in between and using the economies of scale for small generation and storage units, the model of decentralized and local energy generation, storage, and consumption leads to financial benefits. Since the need for renewably generated electricity is unquestionable, and environmental and social benefits are already under investigation by many scientific disciplines, the economic benefit for single actors still needs to be corroborated. This dissertation analyses the causes and effects of Germany's energy transition, the actors involved in the transition and one solution to ensure that decentralized and renewable electricity is financially beneficial in a given market structure.

The overall research question *How are economic, environmental, societal, and technological factors affecting the German energy transition towards decentralization and new market models?* can be answered in two main statements.

First, all four categories of factors have impacts on the energy transition. Furthermore, these factors support or even reinforce each other. However, they can also inhibit each other, so that the process of change is slowed down. As a consequence, actors from all categories environmental, economic, societal, and technical need to work together to keep the transition running. Waiting for a technological leap is not an option.

Second, a way must be found to implement the energy system transformation in an economically sensible way, within the given restrictions and constraints. Currently, the integration of the prosumer as an actor is only financially beneficial, with subsidies and without storage options. This fact depends on the high investment costs, but also on market entry barriers.

Energy communities can be a solution for making the concept of a customer-centric energy supply economically beneficial. This dissertation proves also the economic feasibility of energy communities and offers a way to bring all four categories together into one business opportunity.

5.2 Interplay of Key Findings and Implications of Results

The analysis in this dissertation is split into three parts. First, the regulatory framework and the drivers behind it. Second, the prosumer as one actor. And third, changing market schemes. The key findings have already been presented in earlier sections The interplay of the key findings is important for an understanding of how to design future decisions.

The results show that there is no strong hierarchy among the three layers (structural and regulatory framework, market, and actors) identified, but there is an order of actions taken within the layers. Since the regulatory framework can show opportunities, support ideas or have an impact on economic decisions, the regulatory framework should be introduced by politics, where decisions are made for society. Actors must react to the regulatory framework. This can result in the need to change the business proposition in existing business units, or it can create new business opportunities, such as the prosumer. Since subsidies can only support the development of technologies, a market scheme needs to be adapted. The liberalization of the electricity market in Germany has created a change in the electricity market, and research paper 4 shows how new entities can profit from such market schemes. While research papers 2, 3, and 4 build on each other, research paper 1 gives an overview of the decisions which have led to structural changes in Germany's energy generation. With the results from research papers 2, 3, and 4, further theoretical and practical implications can be derived.

The theoretical implications derived by this dissertation are mainly driven by the idea of decentralization and a changing market model towards a bottom-up market structure. Regulations, both restrictive and supportive ones, can support the change in the market structure and the rollout of new technologies, while the participation of the customer in the energy transition will be enforced. In this way, energy transition can help to establish a customer-centric energy supply by positioning the owner of small and decentralized generation and storage units at the center of business activities. This positioning affects not only major environmental and economic impacts, but also the societal advancements. Smart infrastructures can help to manage electricity generation and distribution and to minimize losses. This will also bring about a system change for energy producers, shifting away from conventional power plants towards virtual power plants or energy communities which combine digitalization and energy generation. From a theoretical perspective, the results of this work enable a fundamental change in the power supply towards decentralized solutions that generate electricity locally and pass it on to consumers. The energy market can thus not only change fundamentally, but future energy supply will be increasingly linked with IT solutions to enable optimal distribution structures.

For practical implications this dissertation implies and promotes a new organization of grid structure and changed roles of system operators. Furthermore, subsidies and programs to support the bottom-up infrastructure can help to faster deploy new technologies, such as PV systems, storage systems or smart managing systems to merge generation and demand in a more effective way. New business models, such as energy communities, will generate electricity in a customer-centric and environmentally friendly manner. As a further practical effect, this dissertation shows the economic feasibility of energy communities when they participate in the energy market. This is a key finding, as it creates new players in the energy sector and decentralizes the energy supply further. Promoting the end-customer-centric generation model by adapting regulatory measures could thus accelerate the energy transition and reduce the costs of the energy transition.

In summary, the interaction of the research papers shows that it is important to understand the different factors which are having an impact on the energy transition. Due to the complex changes needed in a running system, the changes must be an evolution, not a revolution. This is reflected by the interaction of the research papers of this dissertation. The role and benefits of the prosumer, as an actor in a customer-centred energy transition, is analysed for different aspects and factors. The same approach applies to the eventual integration of the prosumers into an energy community. The energy community enables a customer-centred model not on an individual actors' layer, but on a market layer. This has effects not only on the financial profitability of a decentralized generation structure but also on grid stability and management.

5.3 Limitations and Need for Further Research

Since research papers analyse a specific research question under boundary conditions, there are always limitations, which open up space for additional questions and further research. Although, in this dissertation, the four research papers build on each other and a development of the research questions is suggested, three points can be identified as limitations or as a need for further research.

First, it should be noted that this dissertation performs economic calculations exclusively for the situation under German market conditions. Furthermore, the economic considerations of the prosumer are strongly linked to the currently valid rules for subsidies. A limitation of this approach is, therefore, the limited view from the perspective of the actor under given boundary conditions.

Furthermore, the results of the calculation on CO_2 emissions in research paper 3 show that improving the energy mix in the public grid would bring about a better ecological balance than increasing self-sufficiency through higher consumption and larger decentralized storage systems would. This seems to be controversial to other results investigated in this dissertation. But not only does the energy mix in the public grid depend on large power plants, which can be offshore windfarms, but also the space and acceptance of these by the public is limited, which underlines the need for decentralization to support renewable energy generation.

Third, external costs are not considered in this dissertation. This may have two effects. On the one hand, the real price of electricity demanded from the public grid could be higher than charged to the consumer, since for instance CO_2 emissions and other damages to the environment are not included in the price. This could make the installation of PV systems even more beneficial than the investigations show and, furthermore, the investment in battery storage could also be beneficial within the taken considerations, since self-consumption would have a higher financial value. On the other hand, investment prices for PV systems and battery storage could rise as well since these technologies are currently made from complex and hard to process raw materials.

The last point to highlight is the need for further research. This dissertation primarily investigates the economic impact on the asset operators of decentralized energy producers. Here, the focus is on PV systems and battery storage, which have high investment costs. Additional external costs could be included in the economic calculation. The internalization of external costs would take into account the consequential costs currently borne by society, caused for example by CO_2 emissions, and would possibly show the economic advantage of renewable energy more clearly. In addition, a further investigation could focus more on the ecological approach. A life cycle assessment could provide information on whether the operation of decentralized plants has a positive impact on environmental factors. It could also be considered to compare the idea of decentralized generation with large-scale projects for electricity generation, which supports the idea of improving the energy mix in the public grid. For this purpose, new technical solutions, such as a DC underlay grid, could be considered.

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Part B. 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 gained momentum in Germany and further protests have been developing over time, 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 of 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 Background

The long-term development of the transition of the German energy system is of utmost importance for Europe, as Germany has the largest economy on the continent. Likewise, 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 and only reached rank 16 of the Climate Change Performance Index (CCPI) in 2023 after rank 13 in 2022 [5]. In 2020, the target of a 40% reduction in GHG emissions compared to 1990 was only just achieved, and that was just because of the consequences of the Covid-19 crisis, in particular due to significant reductions in the transportation sector [6]. The achievement of the targeted 65% (formerly 55%) reduction by 2030 is so far uncertain [7].

In Germany, currently 489 g of CO_2 are emitted on average 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 [8]. To promote the transition, the regulatory framework has been changed towards a market system favoring 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 [9]. 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 [10].

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 focus of our work is on the transition of electricity generation, as this has played the largest role in the entire energy transition in the long term. Nevertheless, the energy sectors cannot be considered completely isolated from each other as they are interconnected, mainly through common sources (e.g. natural gas). The considered factors are grouped into categories and analyzed according to their cause-and-effect relationships. Their interdependence is analyzed 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 analyzes 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.

In order to gain an understanding of interactions and interdependencies of the complex process of energy transition and to derive arguments for future developments, we examine the following research question:

Research Question
How can the events and effects in the course of the German energy transition be classified with a cause-and-effect analysis and which interactions between the events and effects can be identified?

1.2 Methods

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. In electricity production for instance, France relies on nuclear power in a centralized grid [11]. Denmark already has almost 100% Renewable Energy Systems (RES) in a decentralized grid [12]. 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 [13, 14]. 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 should reach a compromise on the future of coal usage in Germany's energy sector [15].

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 [16].

1.2.1 The Three Pillars of Sustainability and Technological Improvements

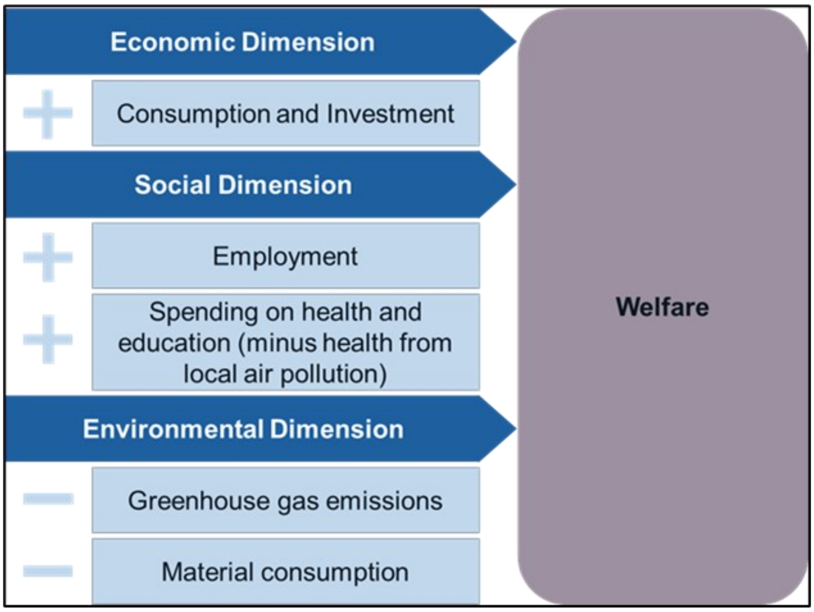

Figure 17: Dimensions of Sustainability (see [16])

Sustainability is, per definition, an integrated concept, which comprises different perspectives [17]. 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 [16]. 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 17.

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 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 relevant topics for electricity generation and supply but also an important issue for the entire economy [18].

The benefits of the energy transition cannot, therefore, be measured only with traditional indicators, such as cost and revenues. Stern et al (2007) already estimated the cost of not acting in terms of the climate crisis to 5% of the global gross domestic product at least [19]. There will also be tremendous impacts on the environmental and social performance of the reformed energy sector [16]. 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 [20–22]. In consequence, it can be stated that all developments during the energy transition can be investigated in the light of public value.

Economic Perspective

The German energy market has been traditionally dominated by few large energy suppliers. Before the liberalization of the energy market these suppliers had defined supply regions without any competitors. After market liberalization, hardly any new competitors were able to establish themselves, partly because the investment requirements were far too high. However, the change in regulations made corporate mergers possible, from which the four large companies that still dominate today – E.ON, EnBW, Vattenfall and RWE – emerged [23].

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 [24]. 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. One example is the so-called energy cooperatives, which, with their local and citizen-oriented character and their focus on the operation of systems for renewable energies, represent a strong antithesis to the large energy companies. Even without the original subsidies and after some regulatory changes, these cooperatives can operate economically successfully and offer a way for civil society to participate in the expansion of renewable energies, in particular, and in the energy market, in general [25].

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 electricity. This market effect will be explained in chapter 1.3.1, especially in the section "Economy - 3) From the Chernobyl accident to the Fukushima accident in 2011", more in detail. 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 Yin and Duan (2022) have shown for China, that coal-fired power plants can support the transition towards a renewable energy system in an economically efficient way [26]. 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 [27]. 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 [28–30].

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 [31]. Regarding the energy system, security of supply and a socially acceptable price level are of particular importance [32, 33].

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 [34]. 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 [35]. 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 [36]. As an outstanding example it can be referenced to the protests of the so called "Last Generation" who repeatedly blocked roads and public places, and could achieve negotiations with municipal governments in certain cities [37]. 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 [38].

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 [39]. 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 [38, 40]. 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 [40–43].

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 analyzed 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 18).

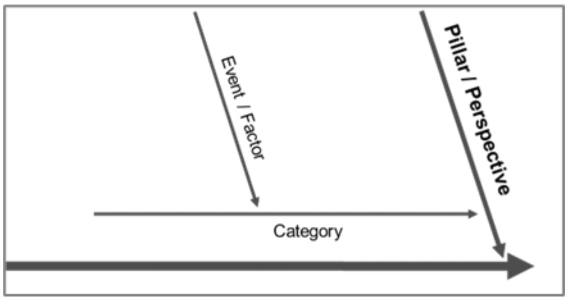

Figure 18: Nomenclature of the Diagram in this Paper

1.2.3 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 events which have affected at least one of the perspectives and can be seen as starting-point, ending or milestone for development. 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 [44]. After a period of economic and social upswing, and triggered by new ground-breaking scientific findings, German 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 [45] and commissioned the pioneering report "The Limits to Growth" from the Massachusetts Institute of Technology in 1972 [46]. 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 analyzed 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 2022

(5) The Russian invasion of Ukraine

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 19 summarizes the relevant events and influence factors for the economic perspective.

Economy

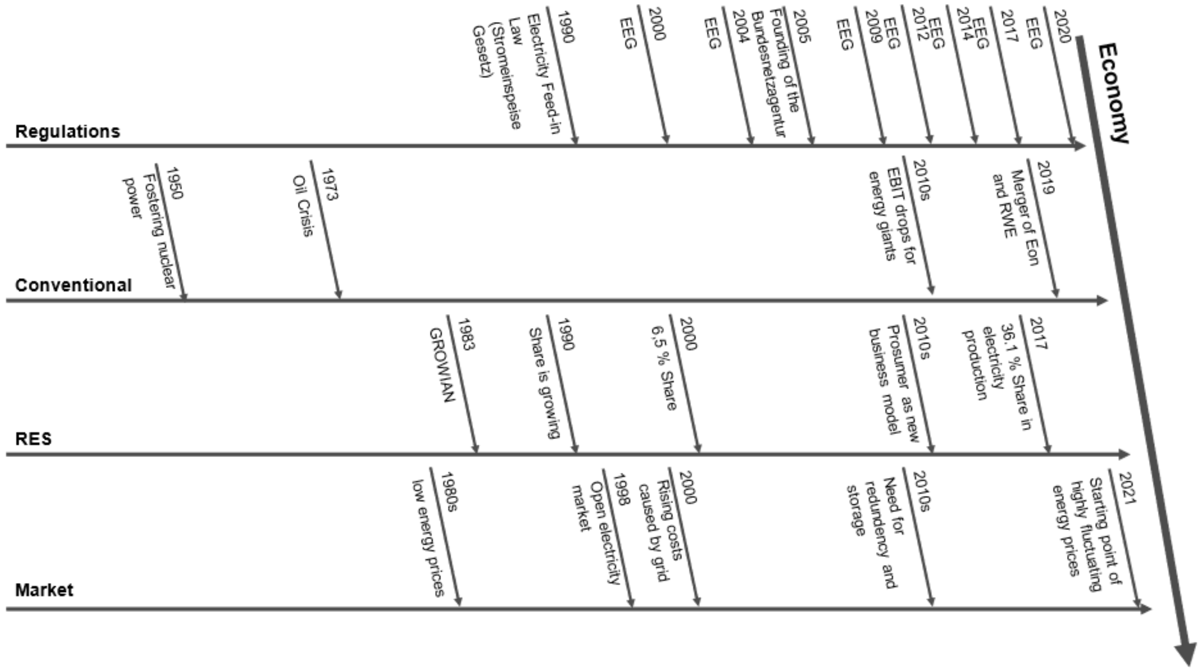

Figure 19: Economic Factors

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 [47] and required large and cost-intensive assets to be utilized over several decades [48–50]. 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 [51–53].

(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 [45]. While industry and politics were able to stabilize the energy production, the price levels for energy in Germany decreased [54]. Finally, in the early 1980s, the price levels for energy in Germany decreased [55], with an energy sector in place that was dominated

by a few large companies running large fossil or nuclear power plants and supplying electricity 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 [56, 57], and which guaranteed an economically appropriate feed-in tariff 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 [58], with the oligopolists being able to maintain their dominant market positions. It should be mentioned that prior liberalization, prices had already been raised considerably to make the effect of liberalization appear more positive. In 2001, only ten electricity suppliers held a market share of 80% in the field of the distributed electricity. During the period following liberalization, the market share of even the biggest electricity supplier in Germany did not change more than 2% over time [59]. 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 [60]. 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 [61]. 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 [60, 62]. 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.

(4) From the Fukushima accident to 2022, 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 [24]. Especially traditional electricity generators have struggled with the new regulations. Conventional power plants are no longer able to operate economically [63]. 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 [64]. Similar changes can also be observed in the other three large energy suppliers [24, 65]. 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 [66]. One reason for that can be seen in the rising share of small-scale units for renewable energy generation, as Figure 20 [67] shows. The share of renewably generated electricity from wind, biomass, solar sources, and water increased from 23% in 2011 to 34% in 2015 and to 46% in 2019.

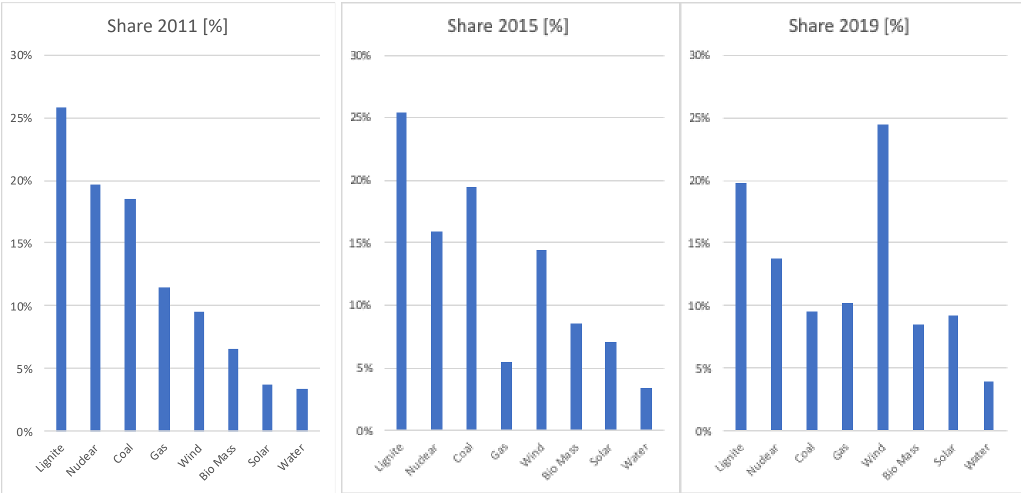

Figure 20: Share of Electricity Generation in 2011, 2015, and 2019

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 the variable costs for conventionally generated electricity. Because of the Merit Order principle, the margins of the large fossil-based power plants have now decreased dramatically. Figure 21 shows the average price per year of MWh electricity on the energy stock exchange in Leipzig [68].

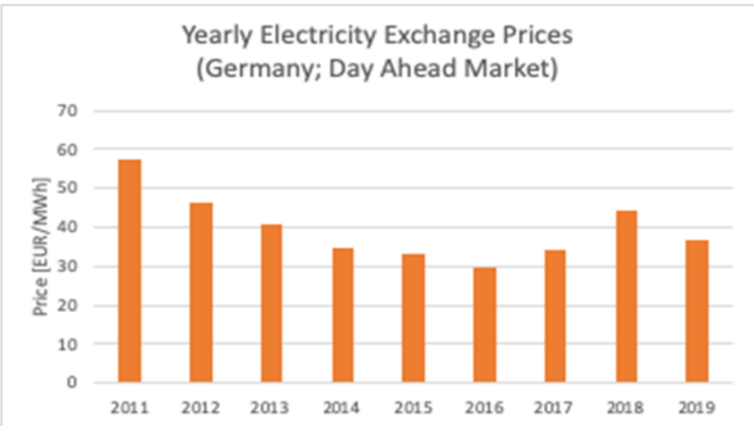

Figure 21: Average Price per MWh on EEX

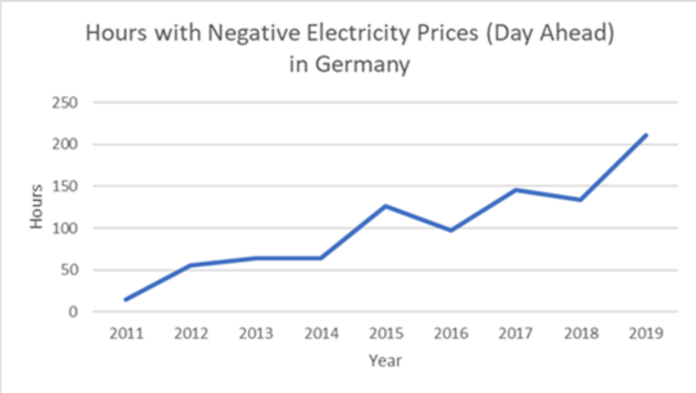

Figure 22: Hours with Negative Electricity Prices per Year in Germany

Additionally, due to the (weather-related) volatility of renewable energy generation units, the price for electricity can be negative at times of high peaks during 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 22). Even if the total share of hours with negative prices is still small, this trend should be noted and may continue in the future with an increasing share of RES. 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 [69]. 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 [19]. In this vein, the energy transition process has also stimulated a transition of the energy supply system which includes the formation of energy communities [25, 70, 71] and the aspiration of many municipalities to take over the local distribution grids [72]. 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 [73].

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 [74]. One reason for this was the increased price for fossil energy carriers.

(5) Russian invasion of Ukraine

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 52% [75] of its gas consumption from Russia, making it the world's largest consumer of Russian gas in absolute terms. 15% was used to produce electricity [76]. EU-wide, 40% of the gas consumed was purchased from Russia [77]. In addition, Russia supplied 45% of Germany's oil imports [78].

While numerous economic sanctions were imposed against Russia after the beginning of Russia's invasion of Ukraine [79], a full embargo of the import of all fossil resources was not possible due to the high economic dependence on the energy sector. In 2018, then US president Trump had accused Germany of becoming totally dependent on Russian energy supply, but these warnings were not heard [80]. 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 [81]. The goal of reducing dependencies on politically less reliable partners came to the fore. The value of independence, or rather the price of dependence, which was almost completely ignored in the procurement of (preferably) the cheapest possible resources, became clear. 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. On the electricity market, disadvantages for buyers due to the Merit Order became apparent as a result of the distortions. The increase in gas prices also caused the prices for electricity from gas-fired power plants to rise. As the most expensive source of electricity, electricity from gas increased the overall market price immensely, especially at times of low production from renewable sources.

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

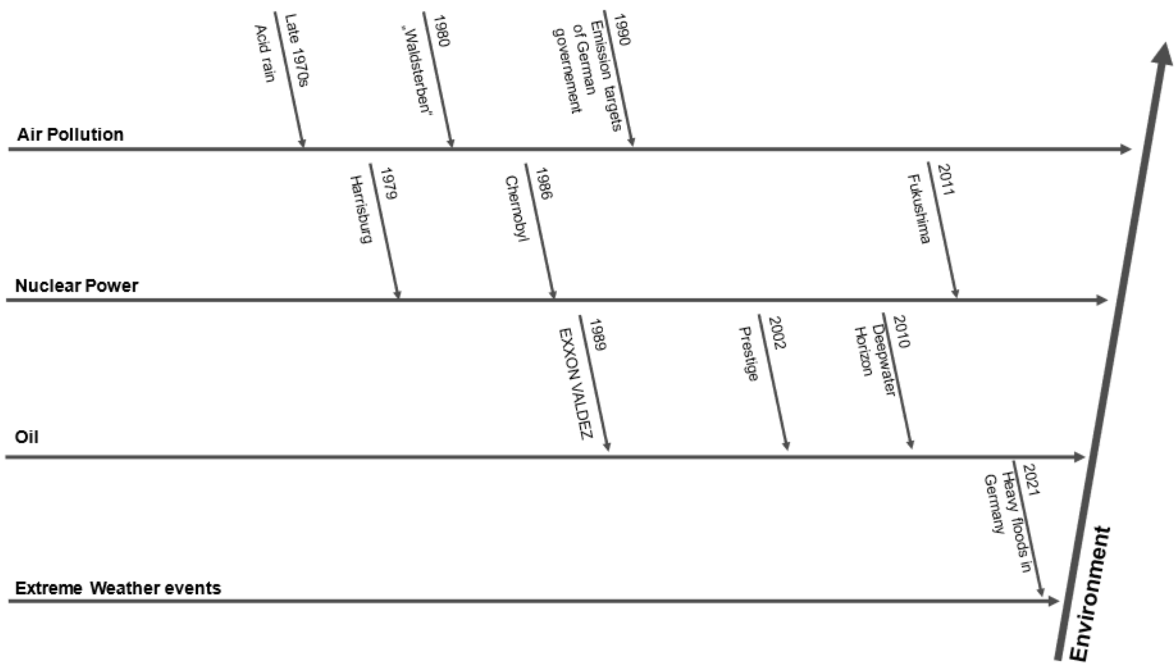

Figure 23: Environmental Factors

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 which consequently leads to the climate change, nuclear accidents, and environmental catastrophes caused by oil.

(1) From WWII to 1968, 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 [51–53]. 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 [82]. 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 [82]. 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 [82].

<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 [45]. It remains one of the biggest nuclear accidents to date [83, 84]. 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 [85]. 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 [45]. On January 18, 1985, smog alarm level 3 of 3 was triggered for the first time [86]. 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 [87, 88]. 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 [89]. 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 [56]. 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 [90]. 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 [91]. 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.

(4) From the Fukushima accident until 2022, no major environmental accident has taken place. Nevertheless, discussion about introducing fracking in Germany is ongoing [92] – 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 [93].

(5) Russian invasion of Ukraine

Concrete effects of the war in Ukraine on the environment cannot yet be fully estimated. Nevertheless, known environmental dangers became evident again on an urgent scale. The threat of bombing and/or sabotage of the largest nuclear power plant in Europe posed an environmental threat not only to the parties directly involved in the war [94].

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 [77]. 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 analyzed 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 [95]. But Figure 24 also demonstrates that, even 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.

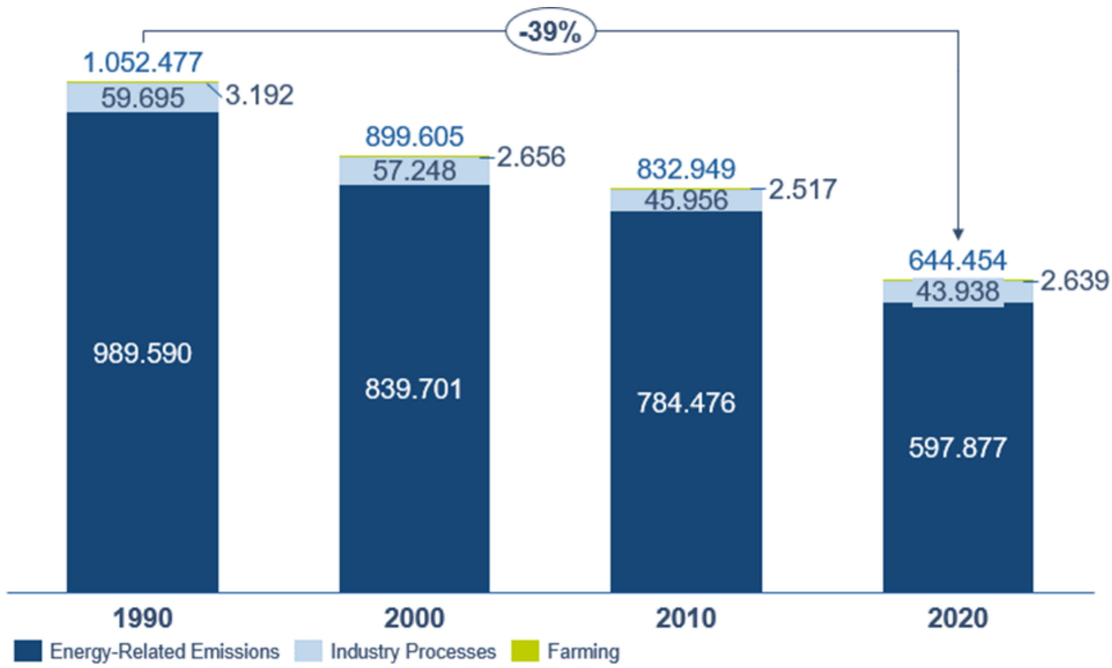

Figure 24: Emissions of CO_2 Equivalent in Germany from 1990 to 2020 [96]

Society and Politics

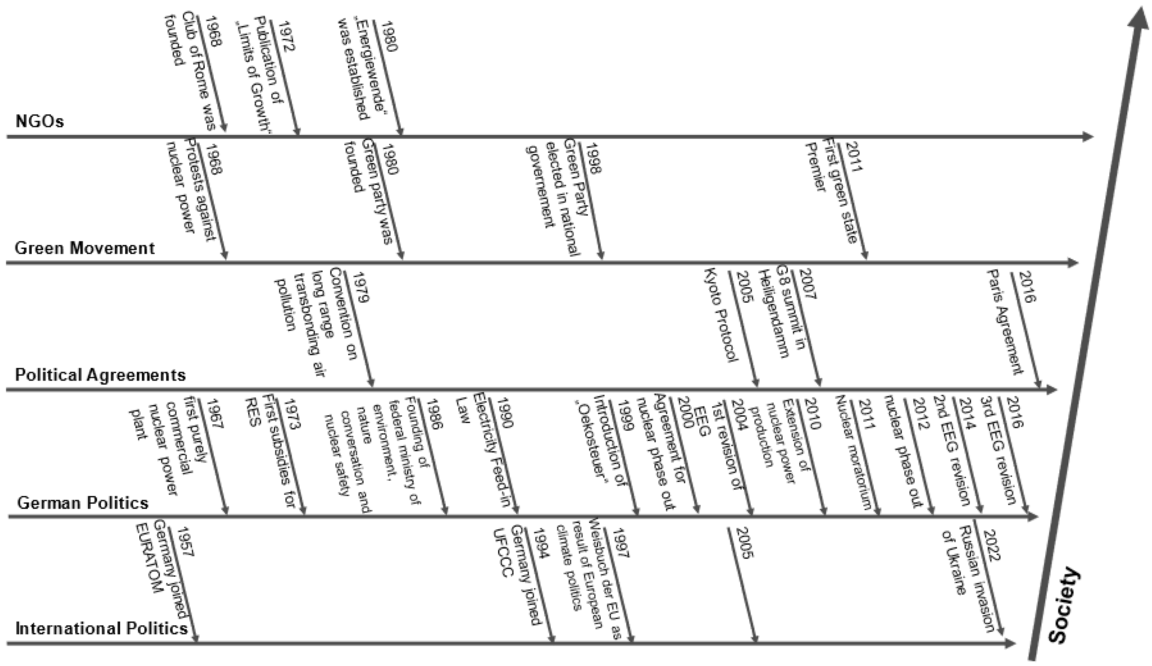

Figure 25: Societal and Political Factors

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 [97]. 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 [98]

<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 [99]. 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 [100], and in 1957 Germany joined the European Atomic Energy Community, EURATOM.

<u>(2) From 1968 to the 1986 Chernobyl accident</u>, 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 [101]. 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 [45]. 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 [44]. 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 [102].

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 [103]. 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 [104], 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. The term was given a further boost by a book from the Öko-Institut: "Die Energiewende ist möglich" ("The energy transition is possible") [105]. The English term „Soft Energy Paths" was coined by Amory Lovins as early as 1976 and was also the title of his publication "Soft Energy Paths: Towards a Durable Peace" published in 1978 [106].

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 [107]. 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 [108]. 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 [109]. 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 [110].

(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 [56]. 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 1992, 20 years after the first united nations conference on human environment, the second united nations conference was held under the headline of environment and development in Rio de Janeiro. The focus of this conference was on the interdependences of the factors of environment, society and economy and how they interact to each other [111]. 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 [112]. 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 [113]. 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 [114].

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 [115]. 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 [57]. 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 [57]. 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 [61]. 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) [116]. 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 [116]. 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 [117].

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 [118]. 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 [119]. 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 [120], companies belonging to the energy sector were most concerned by the EU ETS [61]. 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 [45].

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 [121]. 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 [122].

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 [123]. 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 [61]. 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” [122]. While Germany was already well known for its leading role in the transition of its energy system, (see [124]), some of the regulations implanted during this period did not further promote the underlying processes [122]. However, the political and societal mindsets changed dramatically with the 2011 accident in Fukushima.

(4) From the Fukushima accident to 2022, 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) [45, 125]. 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 [126].

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 [127]. 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% [128]. 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 [45], and the subsequent law for phasing out all NPPs by the year 2021 [129]. 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 26 [128]. 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 [127]. 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 [130]. 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 [131]. 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 [132]. As a result, responsibility for climate protection, among other things, was transferred to the Green-led Ministry of Economics [133].

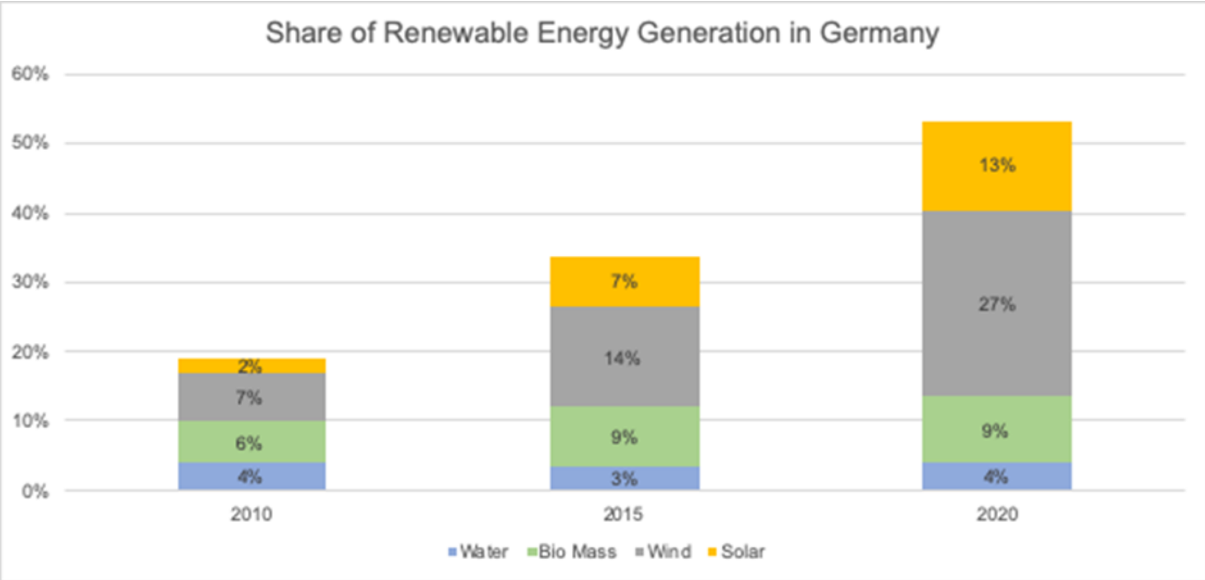

Figure 26: Share of Renewable Energy Generation in Germany

(5) Russian invasion of Ukraine

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 and now the price had to be paid also at the political level. 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 [134]. 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 [135].

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 favour 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.

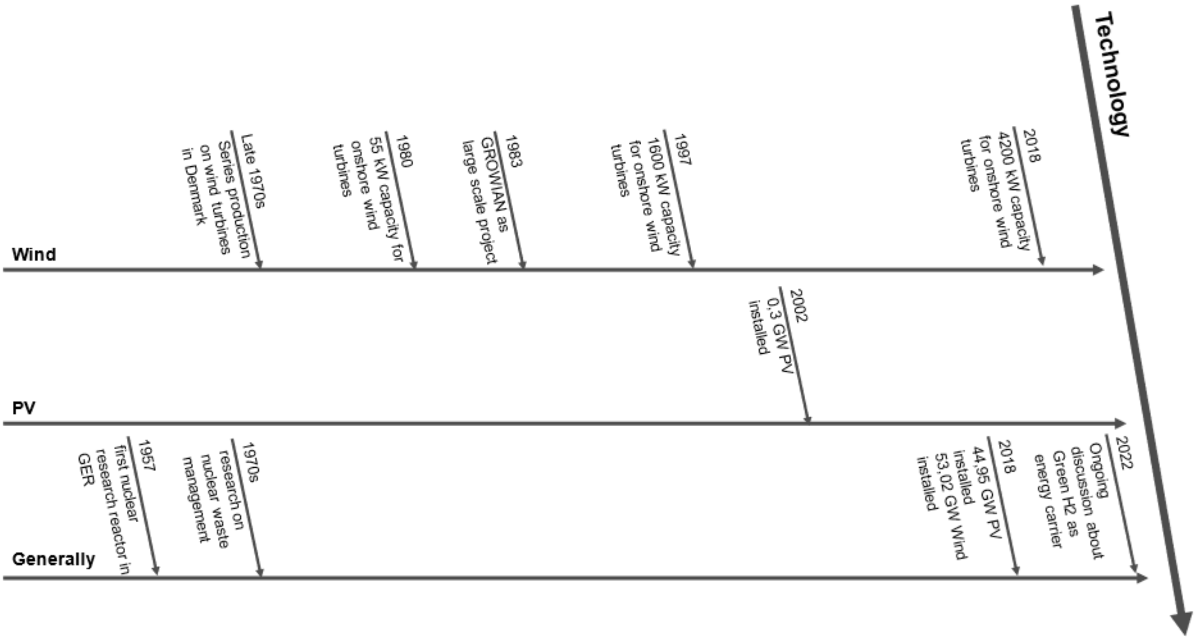

Figure 27: Technological Improvements

(1) From WWII to 1968, 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 [136], and the world's first full-scale power plant with nuclear power opened in Calder Hall in England in 1956 [137], 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 [45, 138]. 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 [139]. 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.

(2) From 1968 to the 1986 Chernobyl accident: After the opening of the first NPPs, the activities of German nuclear research shifted towards waste management and unrelated new technologies such as microelectronics, computer technologies, and environmental science [138]. 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 [140].

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 1970s [45], 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 [45]. 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 [141].

Rapid material fatigue on the blades, hub and rotor brake, among other things, which could be attributed to the design of the plant, meant that the plant was ultimately only in operation on 17 days [142, 143]. In this case, however, the operators, a consortium of electricity companies, were not unhappy with this either, as this project offered good reasons for the continuation of nuclear power for the time being [144].

(3) From the Chernobyl accident to the Fukushima accident, the nominal power 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 [145]. Furthermore, the costs for rooftop PV systems of up to 10 kWp halved in the years from 2007 to 2011 [146].

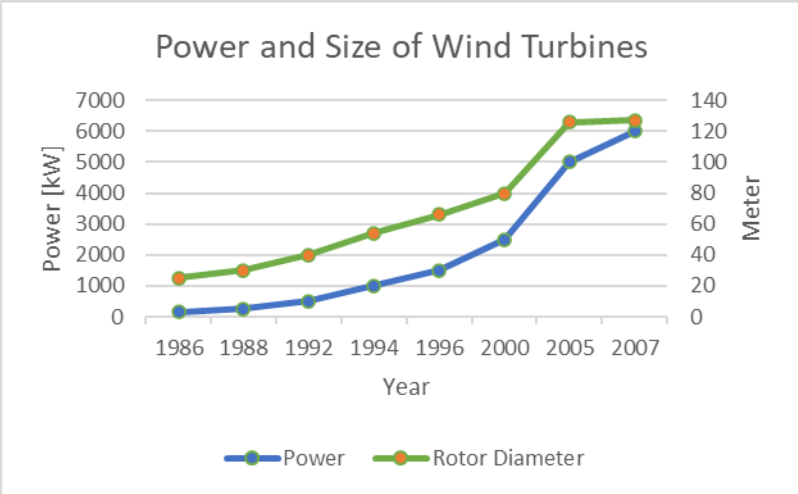

Figure 28: Power and Size of Wind Turbines

(4) From the Fukushima accident to 2022, 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 [122]. 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 [147]. 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 [148]. The current maximum capacity of a single on-shore wind turbine is up to 4,200 kW with a rotor diameter of 127 m [149].

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. [150]. However, it should be noted that Germany will not be able to produce the required amount of hydrogen from renewable energies itself today or in the future. For this reason, Germany is already seeking cooperation with Australia and countries in South and West Africa. In these countries, the conditions are particularly suitable for producing wind and solar power for the production of hydrogen [151].

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

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 [152]. 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 [153]. Hence, the political and economic necessity of an increased energy autarchy might probably 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.

1.2.4 Causes and Effects

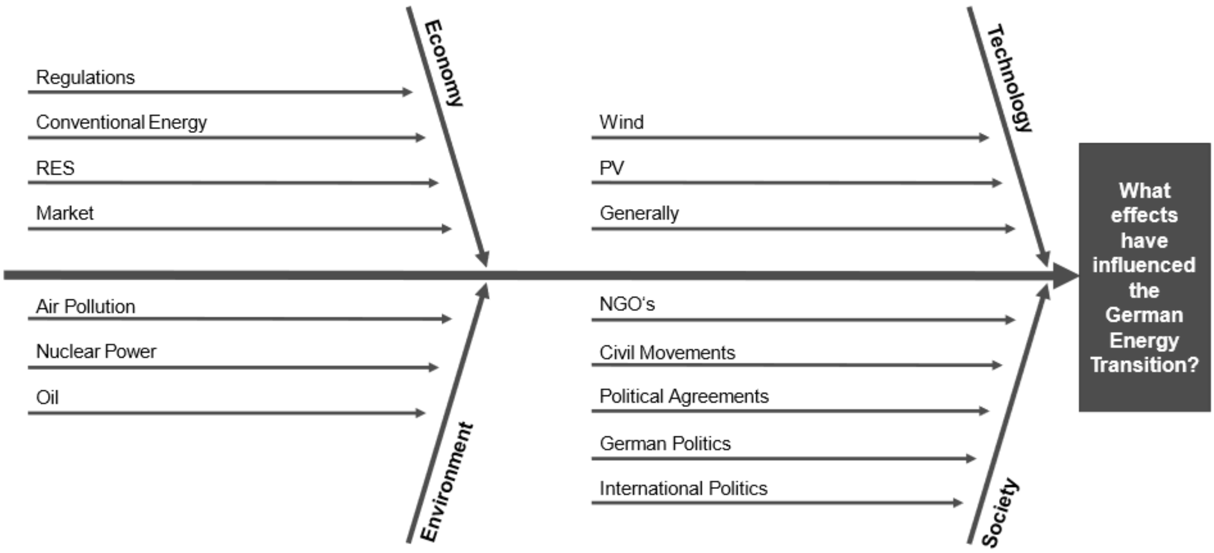

Figure 29: Ishikawa Diagram, Causes and Effects of the German Energy Transition

After describing the relevant influencing factors for the German Energy Transition, the following section indicates 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.

(1) From WWII to 1968: 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 [154]. This change in the political course created a certain amount of economic uncertainty for energy providers and technology companies.

(4) From the Fukushima accident to 2022: 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 in a traditionally conservative region in Germany. 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 2038, a decision which was politically settled – partly due to growing social pressure – after long disagreement. Nevertheless, with “Datteln IV” a newly built coal-fired power plant was put into operation in 2020 [155] which demonstrates the tendency of energy companies to stick with conventional technologies.

(5) Russian invasion of Ukraine

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.

1.3 Results – Categorization of the Interactions and Interdependences of the Different Perspectives

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 neighboring 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 followed the tendencies determined by political decisions and regulations, as well as subsidies for a long time, but missed the chance to properly 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. 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 Discussion and Conclusions

1.4.1 Discussion of the Outcomes and Answering the Research Question

This paper addresses the following research question: *How can the events and effects in the course of the German energy transition be classified with a cause-and-effect analysis and which interactions between the events and effects can be identified?*

Based on our work described above, we can state the following: 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 [156] 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.

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.

1.4.2 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 order to further understand the transformation process described above, one possibility for further research is to complement our work with the application of the multi-level perspective (MLP) by Geels and Schot (2010) [157]. The methodology helps to take into account the complexities, multi-layeredness and non-simultaneities in transformation processes and at the same time to radically simplify them. Changes and dynamics in three levels of action create a space of possibility for transformations. The model is a helpful analytical grid for discussing transformation processes in a structured way. Another method to proof the results of this paper could be the investigation via the method of a quadruple helix approach. Some suggest to add the fifth element of nature [158] which would change the integration of the environmental pillar.

By applying one of these methodologies, the understanding of the German energy transition can be further deepened by taking into account the four perspectives we have identified.

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.

Results & Conclusions

Our research shows that it is financially advantageous for all household sizes to operate the largest photovoltaic system possible for them (up to 10 kWp). 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 30 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.

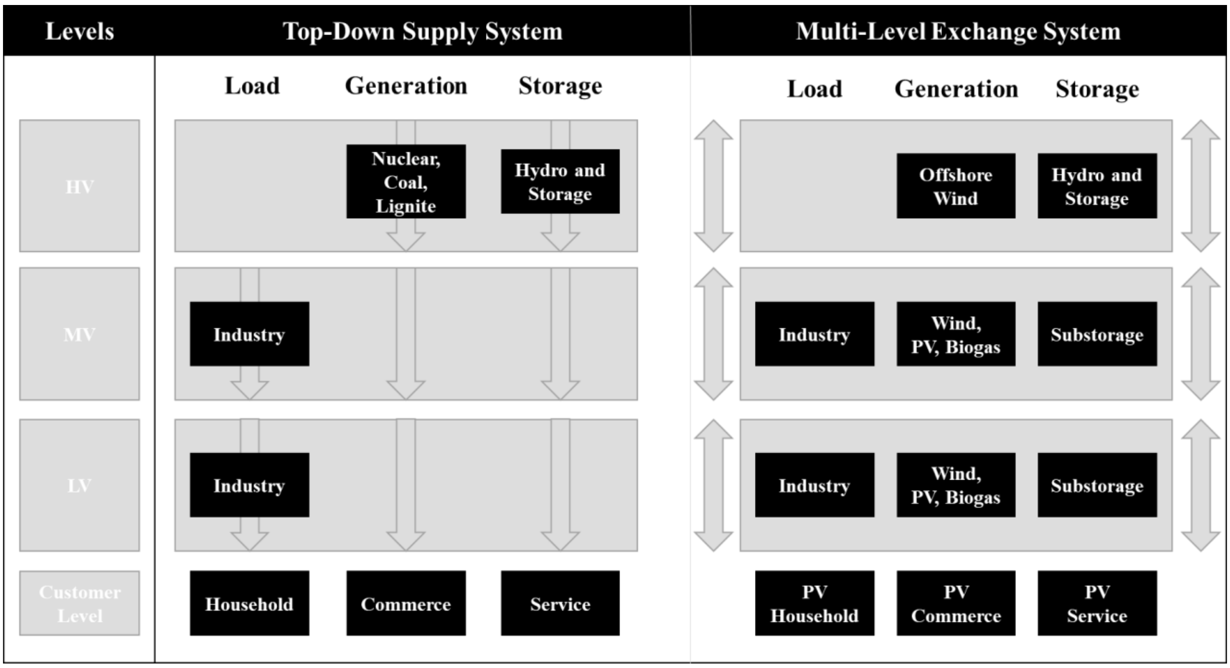


Figure 30: Transformation of the Electricity System [15]

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 31 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 31 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.

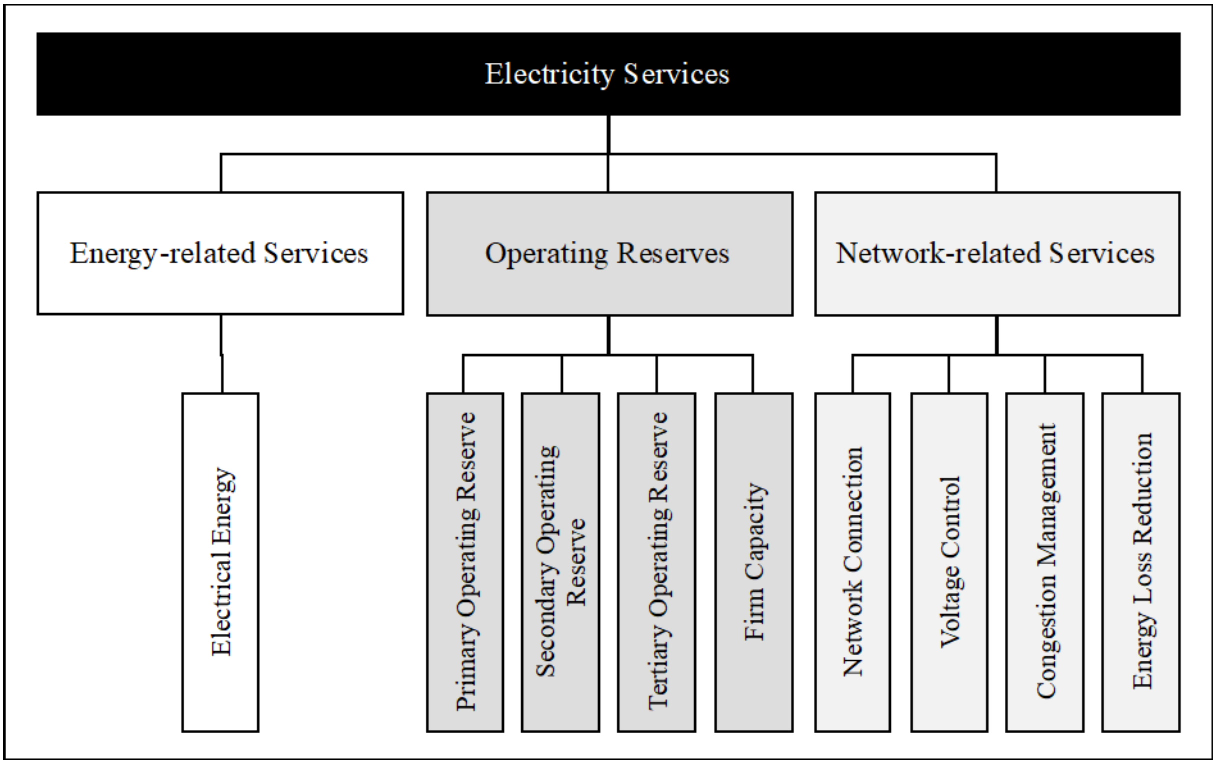


Figure 31: Electricity Services [14]

Due to governmental subsidies and as Figure 32 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].

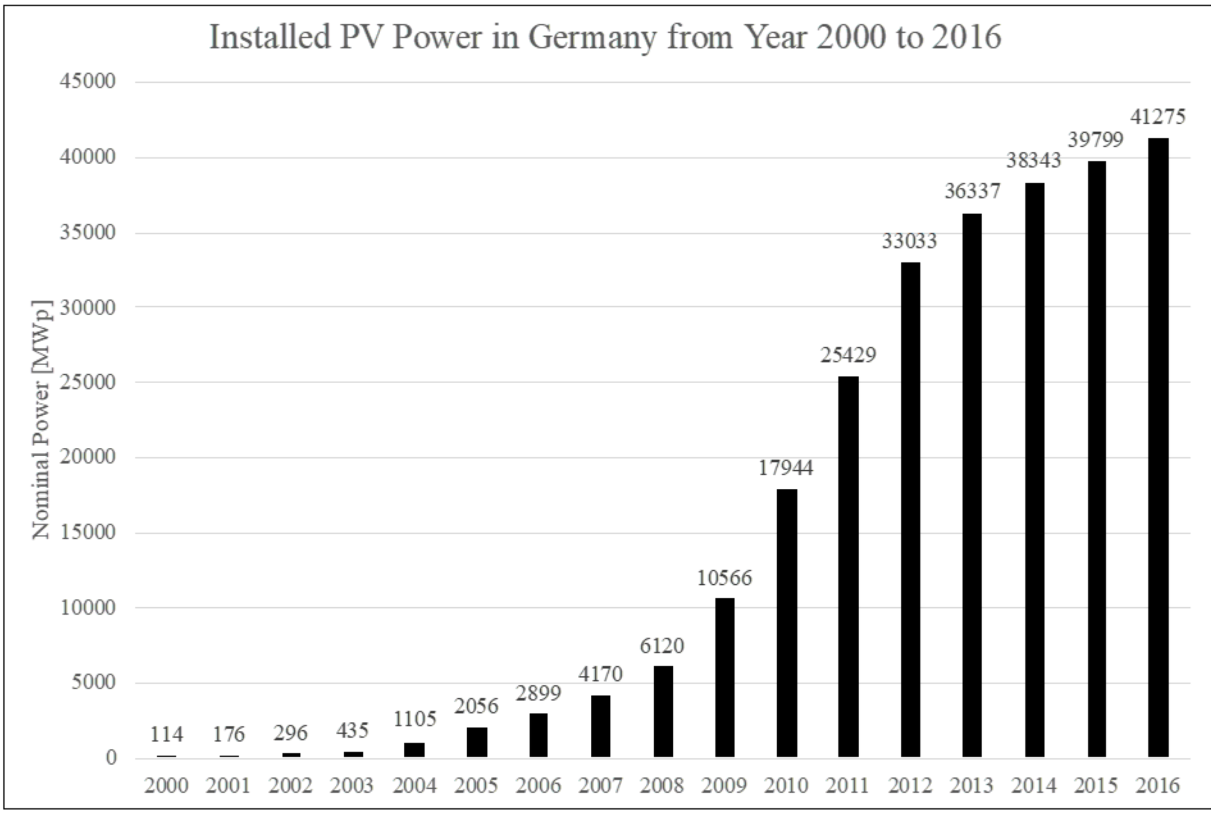


Figure 32: Installed PV Power in Germany from 2000 to 2016

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 Administration		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 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 kWp 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 34.

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.

$$C_{TCO_P} = C_{NPV} \frac{(1+i)^t * i}{(1+i)^t - 1} \qquad \text{(Eq. 1)}$$

C_{TCOp} 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 during the period under review and i is the rate, with which all payments are discounted. We considered the costs 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 33.

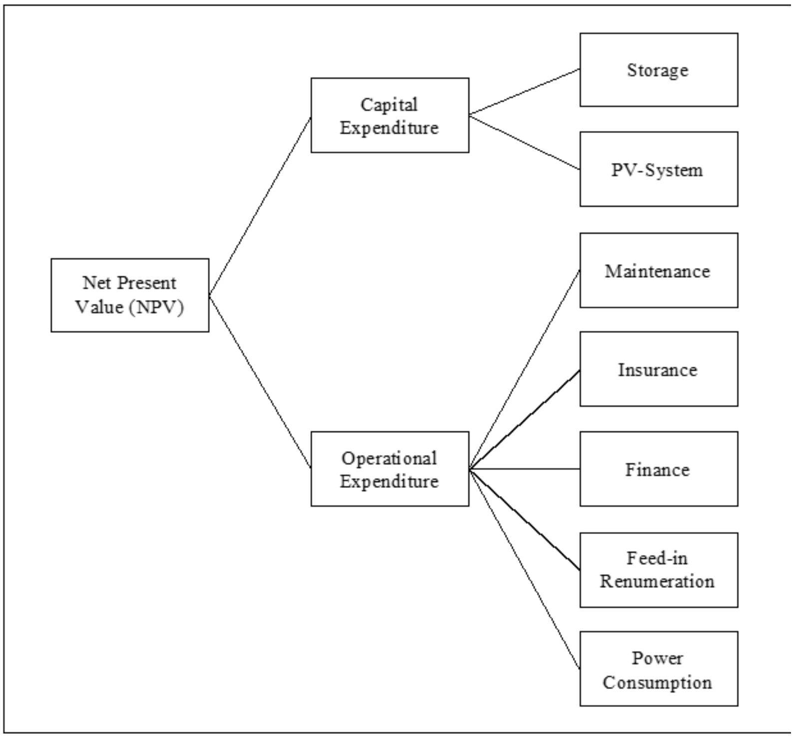


Figure 33: Structure of TCO_P Model

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.

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

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 34.

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.

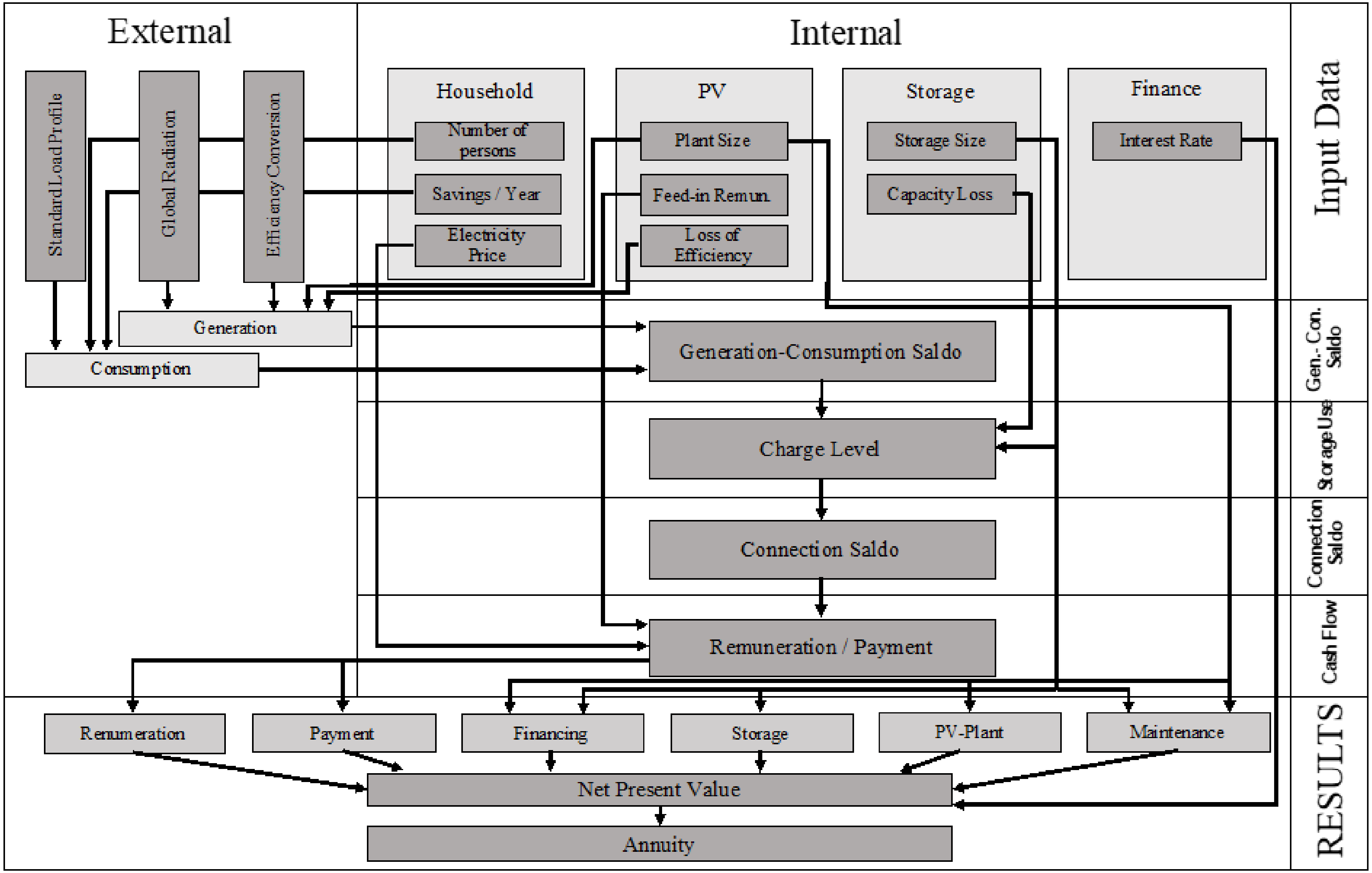


Figure 34: Data Structure

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 2.4.3).

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 kWp 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 3.3.2).

2.2.3..2 Operating Expenditures and Revenues

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 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 kWp 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.

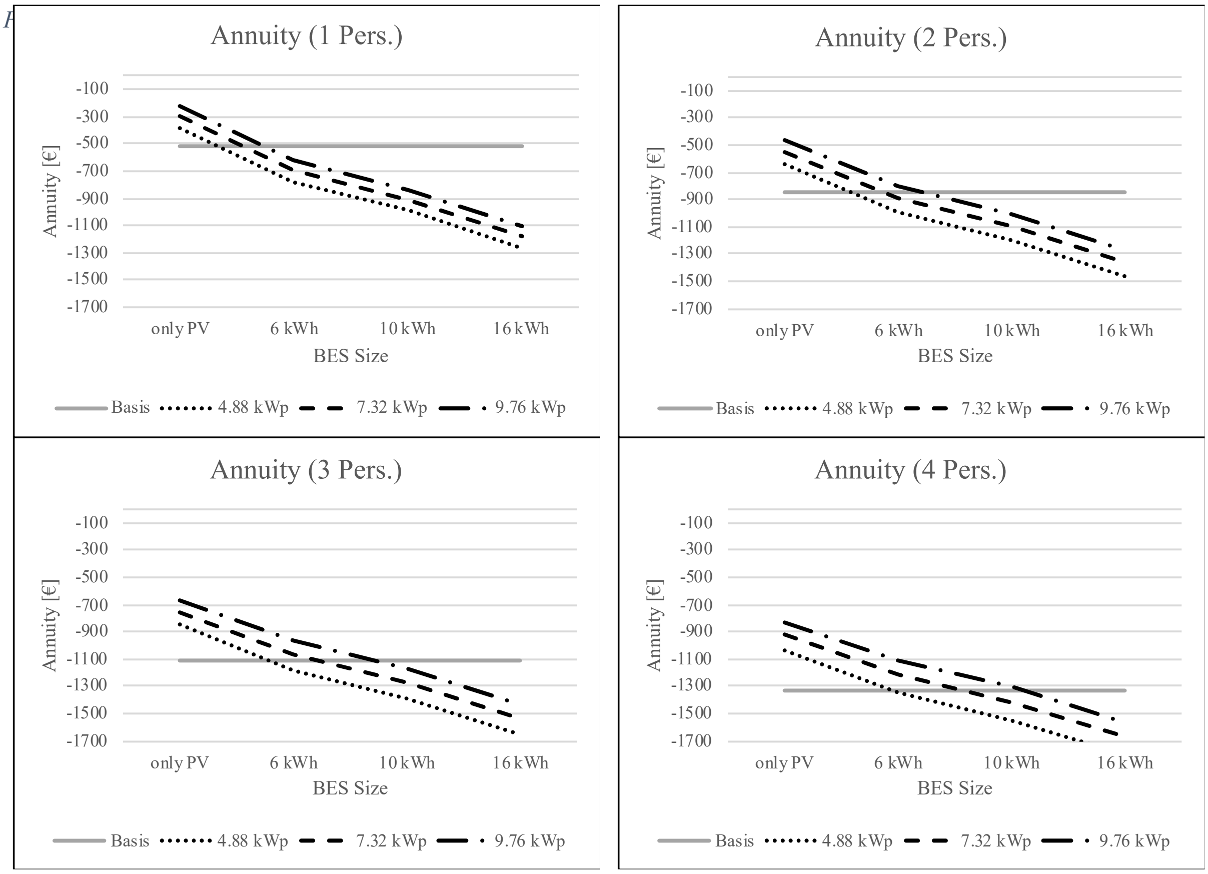
In accordance with this strategy, we map a curve showing the charging level of the battery storage and a data series of feeding-in and withdrawal activities. Those streams of electricity, both the fed-in and the withdrawn electricity, can be assessed financially. Charging and discharging the battery 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 kWp 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 3.2.1 and 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 35.



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 kWp 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 kWp 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 -1323.84 € 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 kWp 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 36 shows three selected scenarios with the variation of the battery storage capacity corresponding to different household sizes.

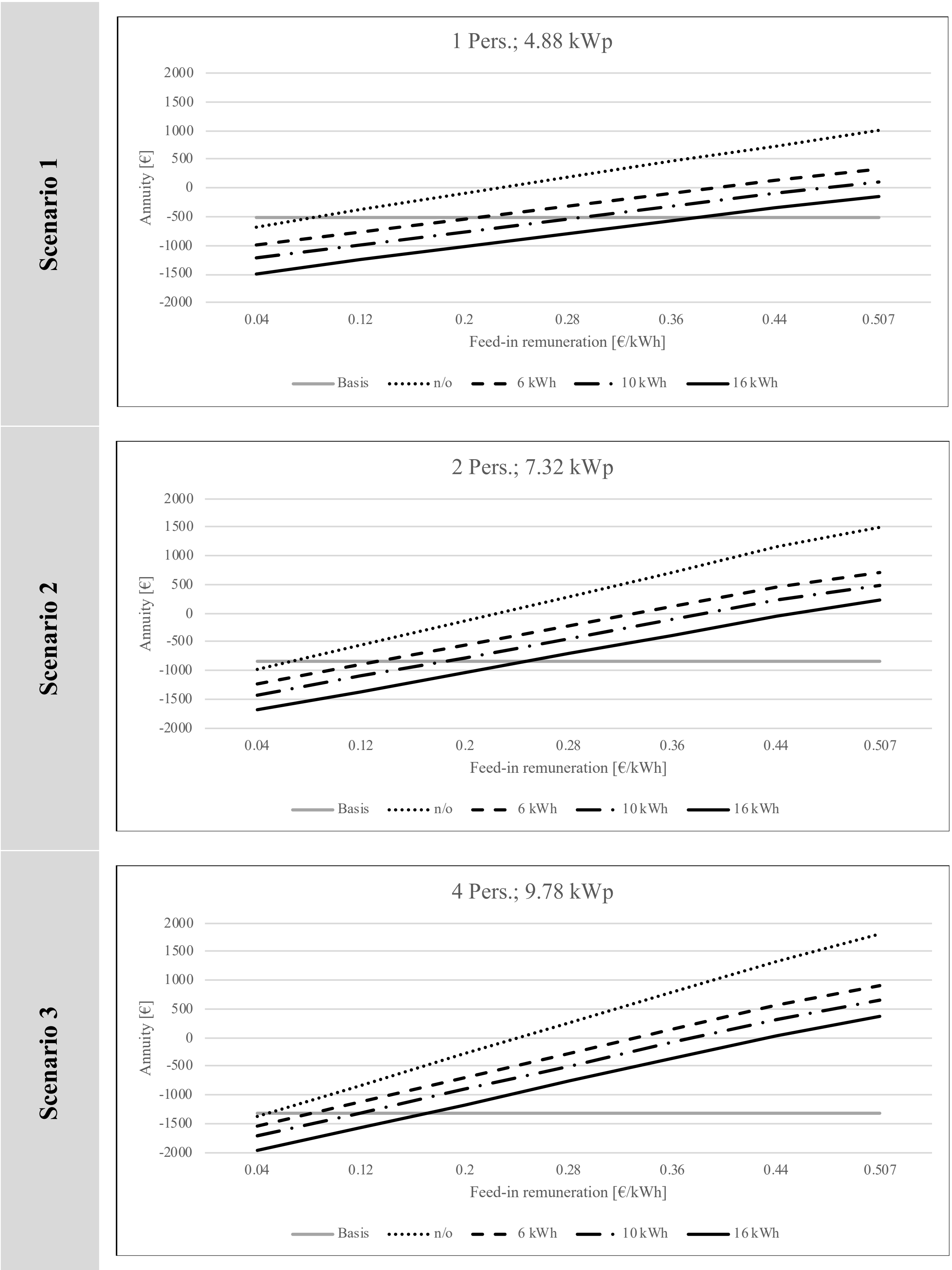


Figure 36: Results Flexible Feed-in Tariff

As Figure 36 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 37 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.

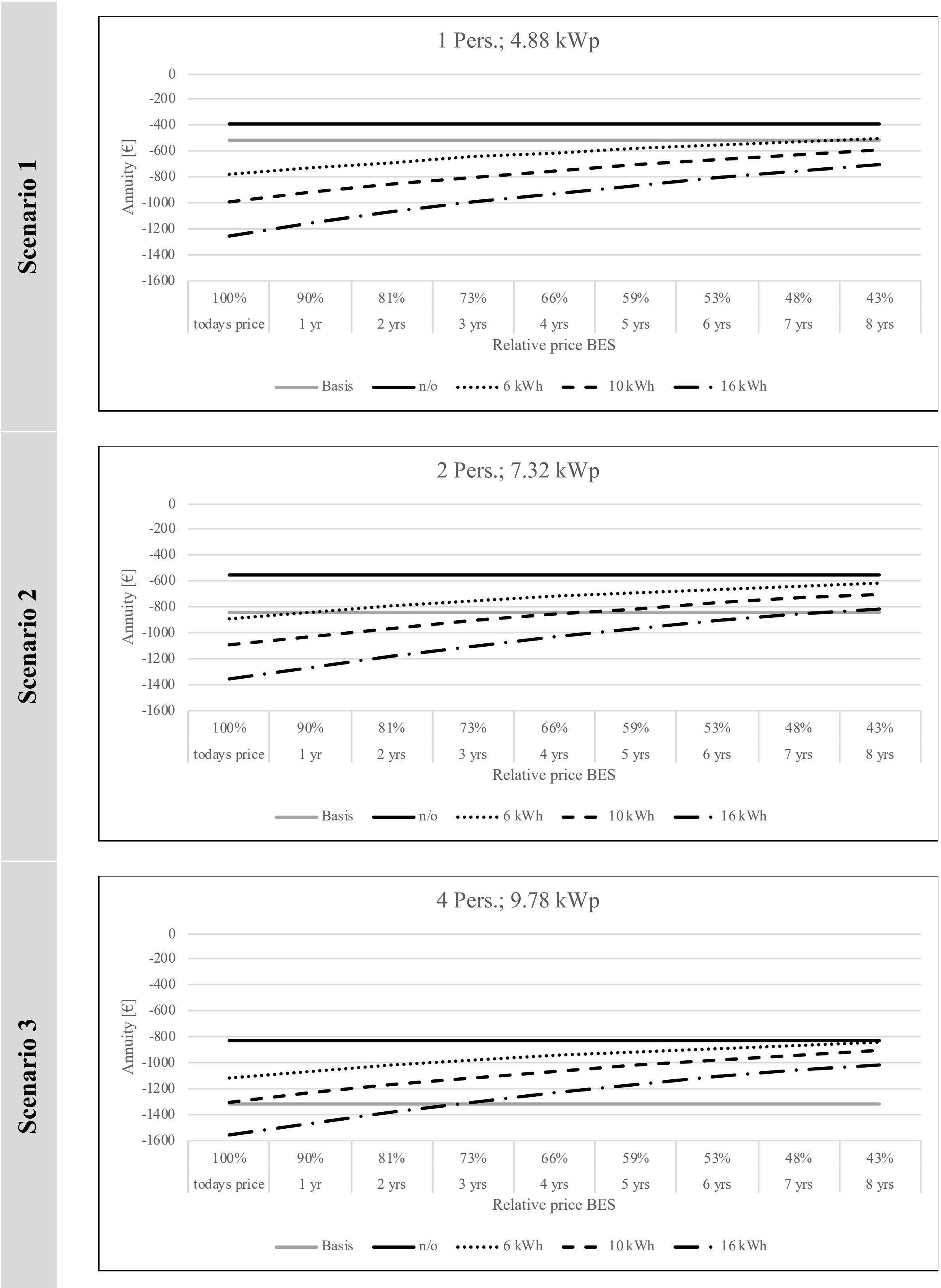


Figure 37: Results Flexible Battery Price

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 38 presents the observed scenarios, detailed data can be found in Tables 11 to 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 kWp; 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 kWp; 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 kWp; 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 kWp; 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 kWp; 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.

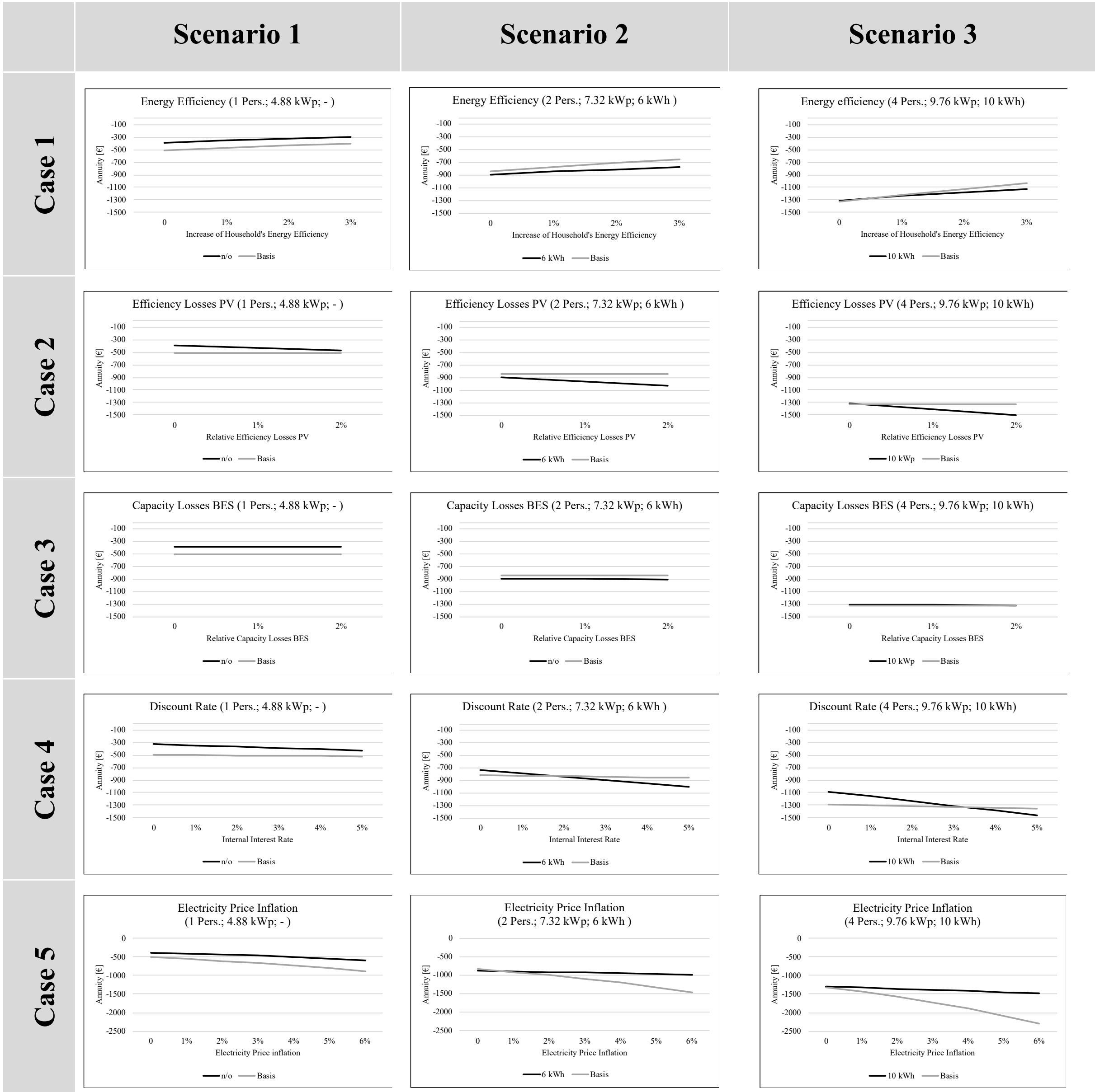


Figure 38: Results Sensitivity Analyses

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

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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 Parameter - 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 Parameter - 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 Improvements

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 - Interest 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 analyze 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.

Key Words

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 analyzed 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 analyze 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 wide-spread 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 Eq. 1.

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

$C_{Capex}$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 Eq. 2.

$$C_{TCO_P} = C_{NPV} \frac{(1+i)^t * i}{(1+i)^t - 1} \qquad \text{(Eq. 2)}$$

C_{TCOp} 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 Eq. 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 40 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 39. 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.

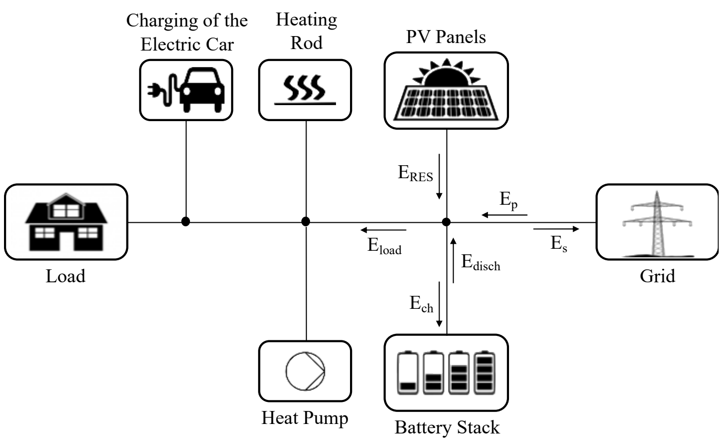


Figure 39: Prosumer Model with Sector Coupling

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.

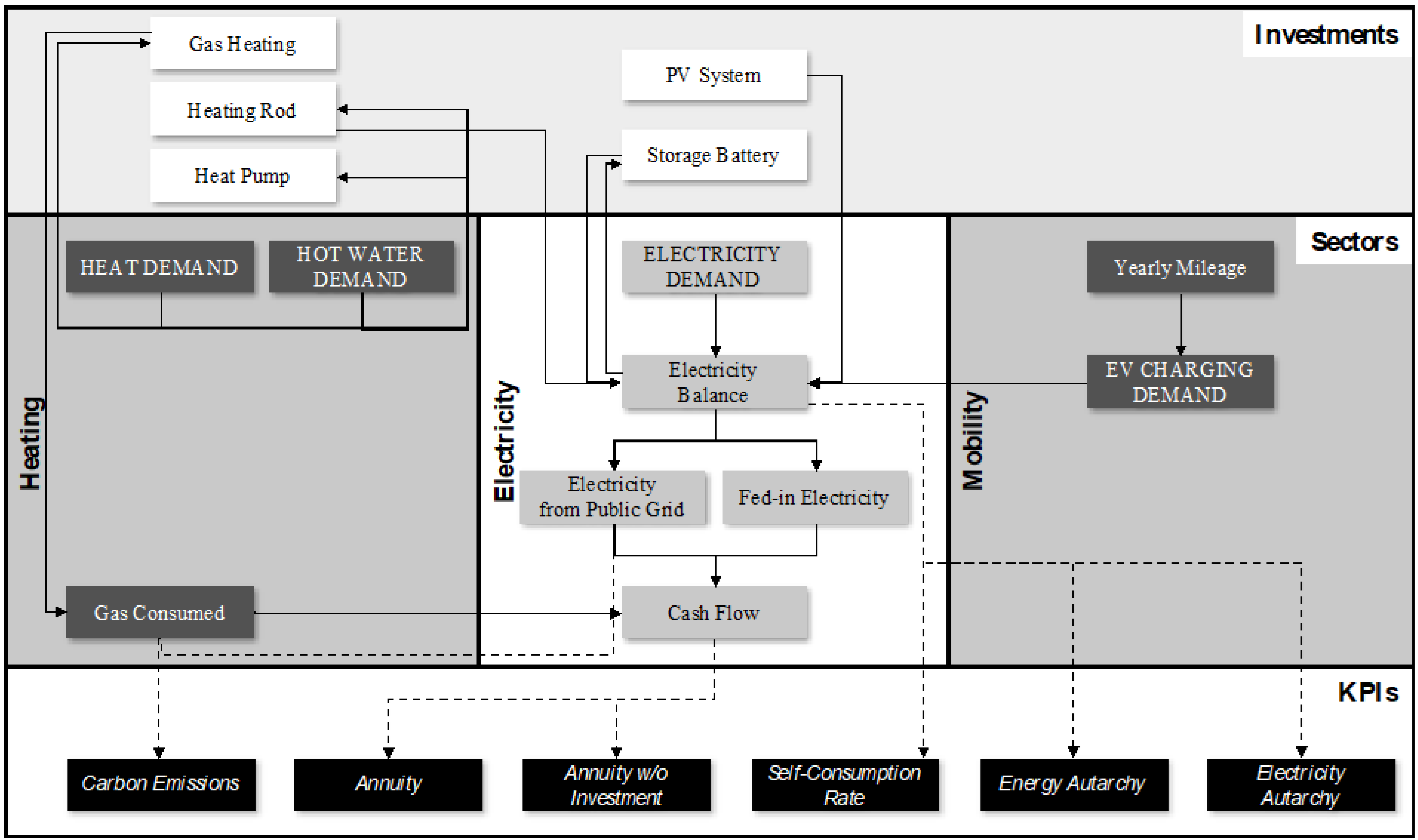


Figure 40: Model Structure

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

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 section 3.7 Appendix of Research Paper 3. In the following we refer to single scenarios by using scenario numbers.

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 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.

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 analyzed 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 41 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 42 below for this comparison.

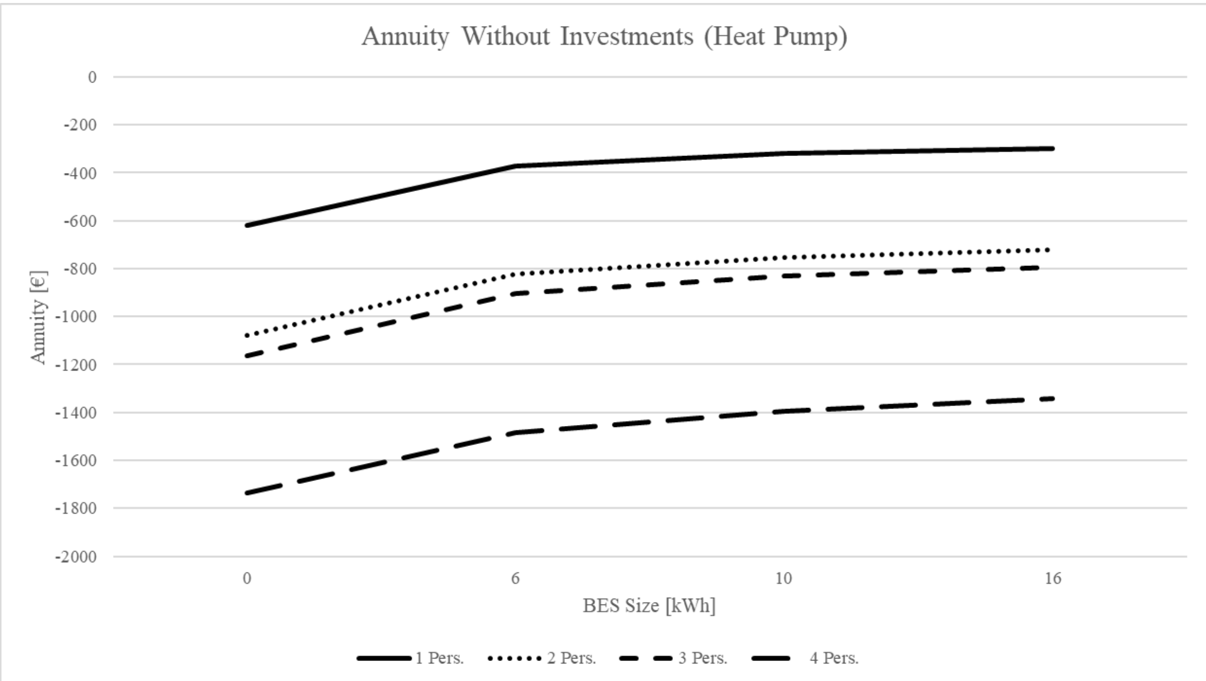


Figure 41: Annuity without Investments

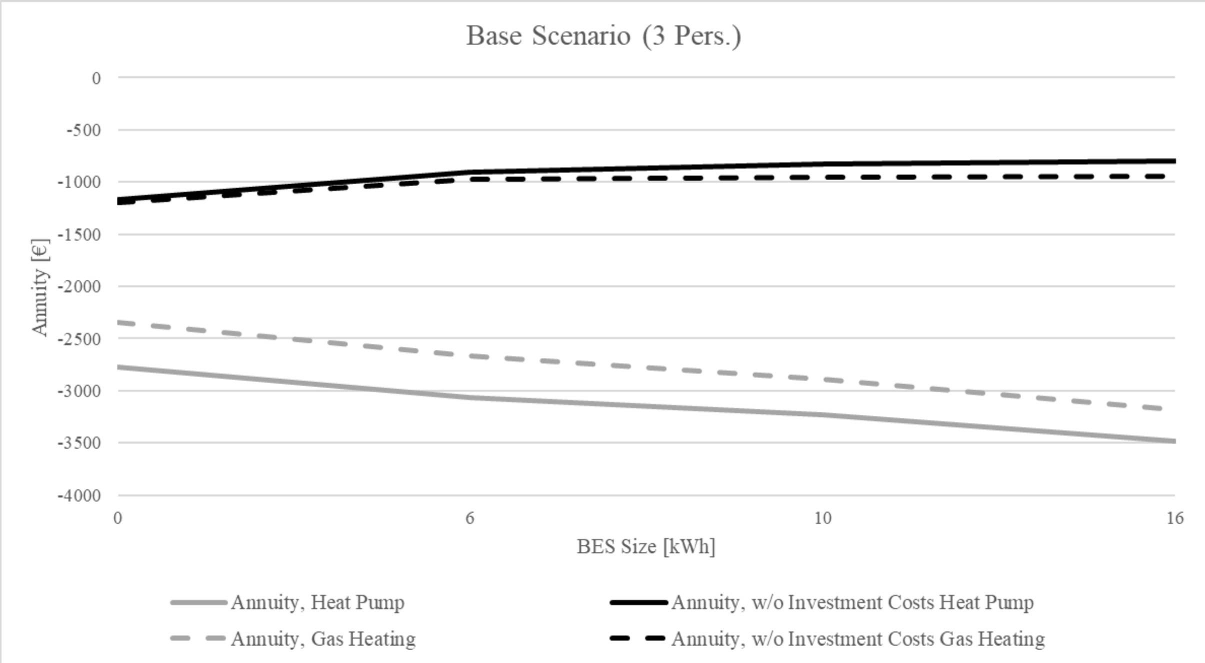


Figure 42: Baseline Szenario - Influence of Investment Costs

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.

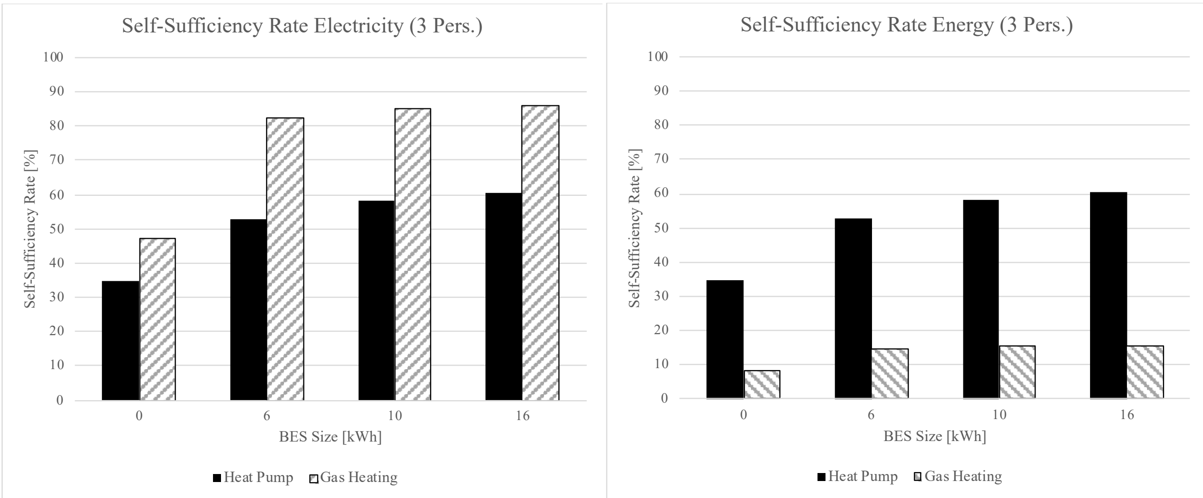


Figure 43: Self-Sufficiency Rate

This is justified by the course of self-sufficiency, shown for the scenarios A9-A12 and A25-A28 in Figure 43. 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 section 3.7 table 18 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 Greening and Azapagic (2012) [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 17 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 44 shows the corresponding annuities of scenarios A9 and A10 assuming a pricing of CO_2 emissions.

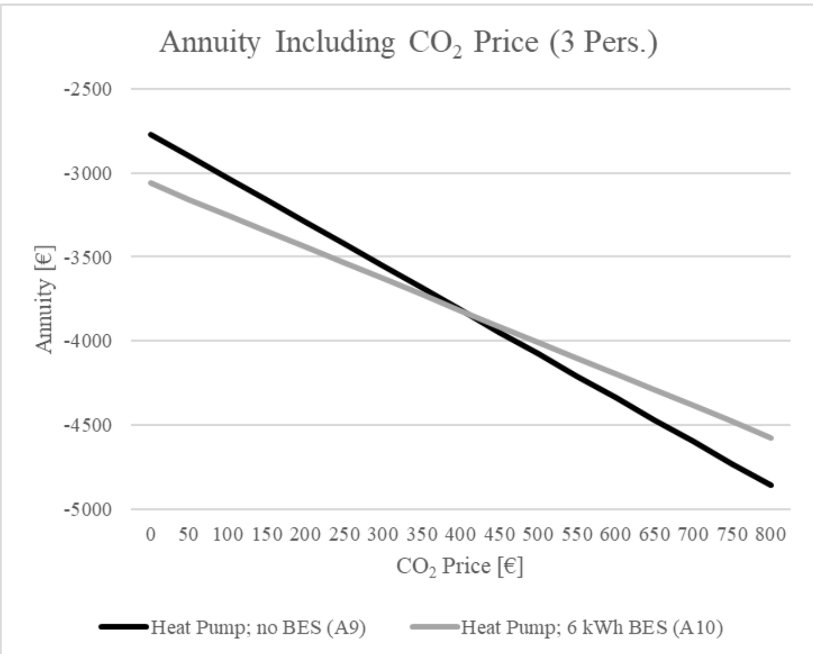


Figure 44: Annuity Including CO_2 Price (3 Pers.) I

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 6kWh 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 45 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.

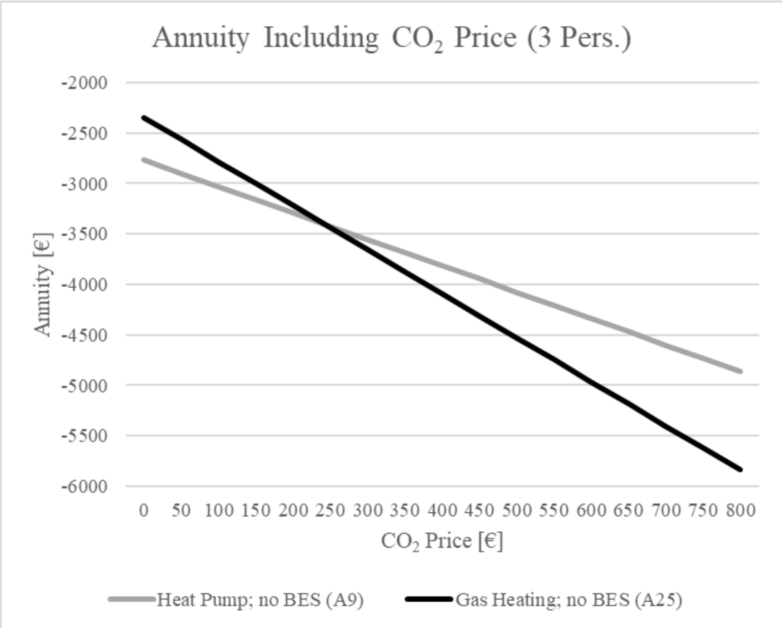


Figure 45: Annuity Including CO_2 Price (3 Pers.) II

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 47 (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 46). This result illustrates that a combination of changes in framework conditions is needed to support the financial attractiveness of BES.

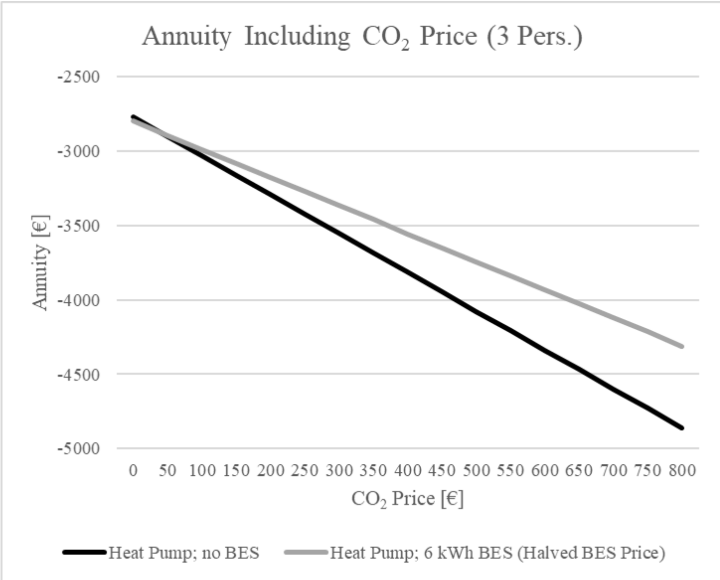


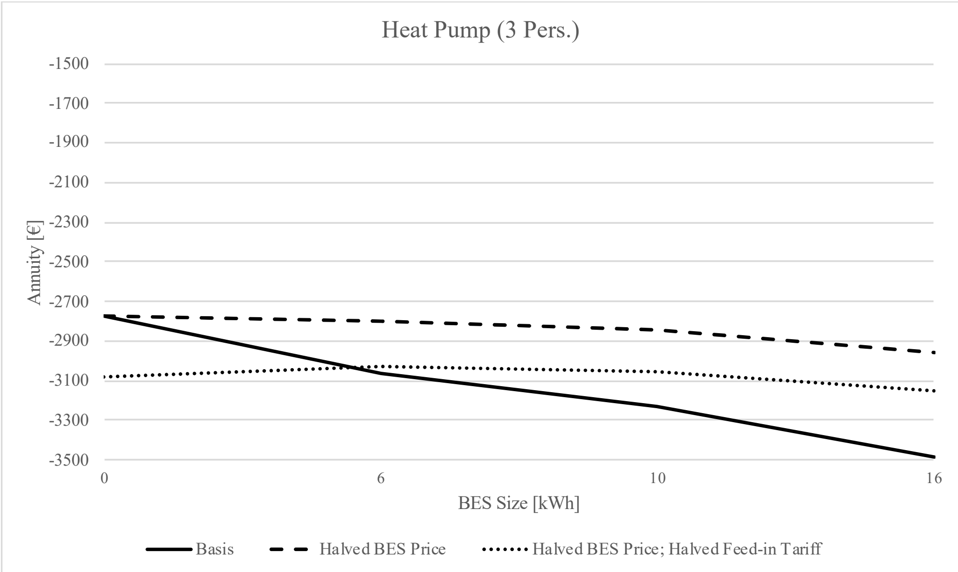
Figure 46: Annuity Including CO_2 Price (3 Pers.) III

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 47 panel A, and owning a gas heating system, see Figure 47 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

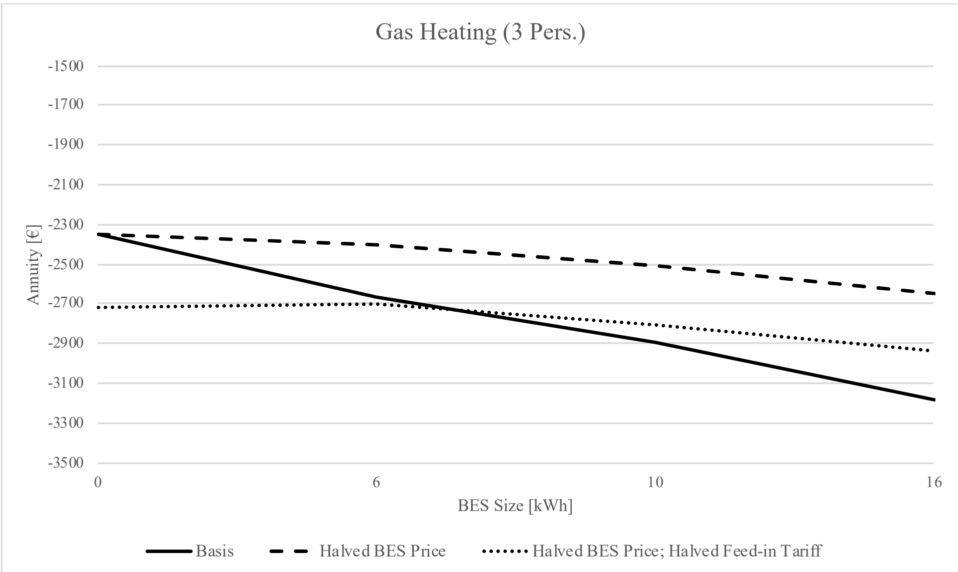


Figure 47: Sensitivity Analysis - Heat Pump and Gas Heating

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 A

	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 B

	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 C

	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 D

4 Research Paper 4: Commercial energy communities participating in the balancing market

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Abstract

Energy generation in Germany is mainly driven by large facilities, like wind farms, and often financed by subsidies. To accelerate the transition of the energy system, business models must be identified for small and decentralized energy generators that are economically viable at market conditions without requiring further subsidies. This paper analyses the concept of Energy Communities participating in the German energy exchange as well as the balancing market. With real-world data the simulation model calculates potential revenue streams for Energy Communities. The results show that Energy Communities are already financially feasible today. However, Energy Communities not only need to be able to generate their own electricity, but they also need storage facilities in order to operate successfully. Hence, investments in local storage systems are essential for the profitable operation of Energy Communities. The simulation model shows how Energy Communities cannot only increase local energy autarchy but also how they can contribute to an increasing share of energy from renewable sources without requiring additional subsidies. We use scenario analyses to validate the effects of various influencing factors, such as taxes or the availability of battery storage.

Keywords

Energy Community, Renewable Energy, Battery Storage, Market Simulation

4.1 Introduction

The accelerating climate change and movements such as Fridays For Future make it clear that the abandonment of fossil fuels has to be promoted on a broad basis. In Germany, electricity generation from renewable energy sources (RES) rose from 122 PJ to 1,056 PJ from 1990 to 2021[1], while during the same time span generation from coal fell from 3,066 PJ to 1,437 PJ and generation from nuclear power decreased from 1,663 PJ to 754 PJ [2].

It is beyond dispute that 100% energy production from RES requires further investments in generation and storage systems. Photovoltaics (PV) plays an important role for the expansion of renewable energy generation. Already today, 7% of the electricity supply is generated by PV [2]. Between 2000 and 2018 the capacity of PV systems in Germany rose from 0.114 GW to 45.277 GW [3][4]. Even though it is controversial how much PV potential Germany has, estimates between 200 GW [5] and nearly 300 GW [6] are much higher than the maximum potential of offshore wind farms, which is assumed to be about 85 GW [7]. Furthermore, offshore wind farms are more cost-intensive compared to PV [8].

Although these numbers show that energy system transformation has already made substantial progress, it is far from being a complete. For example, the German government's targets [9] to reduce the emission of greenhouse gas (GHG) emissions can only be achieved if renewable energy production is further expanded. In this vein, Mattey and Bünger [10] estimate the external costs per ton CO_2 of € 180. The UN assumes that the costs to minimize the consequences of climate crisis for not acting are at least 5% of the global Gross Domestic Product [11]. Hence, even from a purely economic perspective, the stimulation of new business models that are draw an RES is advisable. However, the financial burden created by the costs of the transition of the energy system for private customers should be taken into account when implementing market models which add value to society as well as to the market participants. At the same time, former energy consumers can be transformed into prosumers, e.g. by investing in PV and battery storage systems. Decentralization and modified grid structures for involving prosumers in the generation process will therefore play an important role in the future [12], but will also generate additional costs. These related costs and benefits for the prosumers can likely be influenced positively by creating Energy Communities which “collective energy actions that involve citizens’ participation in the energy system” and “can be understood as a way to ‘organise’ collective energy actions around open, democratic participation and governance and the provision of benefits for the members or the local community.” [13].

This paper introduces a market model for prosumers which is merged to Energy Communities within today's German market conditions. Calculations are based on real market data and designed to optimize the financial result in favours of the Energy Community participants. Furthermore, the resulting business models create added value to society by offering electricity and capacity to the balancing market when available.

A rising share of generating energy from RES also requires storage systems. Because of the volatility of renewable resources, substantial backup is needed. Even though scarcity of electricity is generally not the problem, supply and demand peaks are difficult to balance [14]. Depending on the results of different studies, the estimated required storage capacity varies [15]. Hartmann [16] calculated a necessary storage capacity for Germany of 83 TWh when the energy system fully relies on RES, but only 6.3 TWh capacity for a 80% renewable scenario. Child et al. [17] estimated up to 147 TWh storage capacity for Germany caused by grid fluctuations. Others, like Sinn [18], expect only a demand of 16.3 TWh electricity storage for Germany for a 100% renewable scenario.

Assuming that PV generation will account for a significant share of renewable energy production [19] and the need for storage systems rises [20], decentralization will become more and more the focus of future energy systems and its grid structures. Prosumers can play an important role in this decentralization and further increase their share in energy production [12]. This can help to reduce CO_2 emissions [12, 21] by increasing local self-sufficiency [22], but also requires local generation and storage systems [23]. Furthermore, large variances exist between the requirements on storage systems, regarding their technical requirements for instance in terms of the capability to provide balance power [15].

Nevertheless, decentralization can help to improve and stabilize the energy supply. Pioneering the research in this area, already [24] analysed the benefits of a small local energy grids. Likewise, other studies developed and analysed decentralized PV and storage driven systems [25–27]. However, the focus of these analyses was primarily on the technical feasibility and the idea of part-time islanded solutions not embedded in the overall energy system [25].

Yet decentralized energy generation and storage solutions on a small scale are "interesting not only from a technical, but also from an economical perspective" [28]. Locally generated and stored energy can buffer gaps in demanded and generated electricity [28, 29] and, thus, increase the share of renewable energy. Micro-grids are already a valid option on the low voltage level [28] and can relieve the grid and reduce the number of blackouts and failures [30]. With rising numbers of trading activities on the European energy market (from 63 GW to 262 GW [17]), a reliable and stable distribution grid has become more important than ever.

Despite the introduction of micro-grids, regulatory measures are still necessary [12]. Considering, that even with an increasing efficiency the energy demand of households rose from 2,383 PJ to 2,430 PJ in total from 1990 to 2017 [31] and the energy demand of the mobility sector increased by almost 376 PJ during the same time span, it becomes apparent that the update of regulations and new techniques are mandatory to achieve climate goals. In particular, further economic incentives can stimulate energy savings [32] and smart consumption patterns. By taking these aspects into account, this paper analyses the current revenue and cost structures of Energy Communities and develops a business model which allows market participation not only in the Day-Ahead Market, but also in the Balancing Market. Considering levies, taxes and fees the research question

Does it pay off financially to run an Energy Community which operates on the Balancing Market under German market conditions?

will be answered.

4.2 Changing energy markets towards Glocalization

The term "Glocalization", first mentioned by Robertson [33], is used to describe the local impacts of global trends [34]. Glocalization does not only focus on the consequences of globalized market on local communities, but decentralization (localization) can also counterbalance negative influences of globalization such as technological and economic dependencies, weakening of social systems and pollution of the environment. With regard to energy systems, higher levels of autarchy and stable cost structures combined with energy from renewable resources can be promising avenues. For this purpose, techniques, regulations, and interconnections have to aligned toward decentralized energy systems in the one hand. On the other hand, implementation and sub-systems have to be realized on the local level to enforce renewable energy generation, especially with PV. These fields have to be developed simultaneously [35]. While this paper focusses on the local dimension, global regulations and context are considered. Especially since the end of 2021 energy prices are subject of high volatility and with an eventual gas shortage in Germany, the electrification of the heat sector is accelerated, this topic is even more relevant.

The following sections introduce recent data and studies dealing with decentralized Energy Communities and different variations of micro grids and virtual power plants are explained. This literature review is used to develop a model for the Energy Communities and the related simulations in the third chapter. Furthermore, it is important to introduce concepts of the regulatory framework which are needed to understand the status quo and which adjustments could and should be made from the regulatory perspective.

4.2.1 Need for Decentralization

In 2018 every generated kWh of electrical energy in Germany emitted 489 g CO_2 on average [36]. There is no doubt that emissions from electricity generation have to decrease not only in total, but also per generated kWh. This can be realized by increasing the share of PV-generated electricity systems. In 2010, PV systems had a share of 9 %. However, 40 % of the subsidies according to the Energy Conservation Act (Energieeinspeisegesetz, EEG) were paid for photovoltaics [37]. Since then subsidies decreased step by step and the efficiency of PV systems rose [38]. Nevertheless, this development must also be supported by an expansion of energy storage systems [37] to provide solutions for times without electricity generation, for instance at night, and to balance the grid if necessary.

The investigations of this paper become even more important, since decentralized generation and consumption schemes can not only help to reduce the CO_2 emissions [12, 21], but also pave the way towards smart-grid solutions [23]. In addition, decentralized energy generation additionally reduces transmission losses [39], which also means savings in energy generation in combination with an adequate plan for decentralized storage and consumption [40]. Furthermore, decentralized solutions can help to support the security of energy supply [41] and reduce the number of incidents in terms of voltage drops [42]. For local grids, only short low voltage power lines are required while huge centralized systems require larger infrastructure, even on low voltage level [43]. This makes small-scale energy generation, storage and consumption interesting also from the financial perspective [28]. Participants in Energy Communities can also realize a higher degree of energy autarchy, a topic which has become even more prominent due to recent political events [44, 45].

The decentralization of the energy generation needs a broad participation of the new actors, like prosumers or Energy Communities, and established actors, like system operators. These actors have to be well-coordinated with each other [46–48]. Kappner, Letmathe, Weidinger (2019) [49] already showed that being a prosumer can be financially beneficial with fixed incentive schemes and under changing investment conditions, such as lower battery investment costs.

However, a financial benefit of the use for only private reasons for battery storage systems under German market conditions, incl. subsidies for fed-in energy, highly depends on given circumstances and is not guaranteed [29, 49]. Even though, other market frameworks and decreasing investment costs for the batteries can make settings including battery storage systems financially beneficial [50]. In contrast, PV systems still can be an attractive investment with lower incentives since the average purchase price of electricity was 0.2916 €/kWh in 2017 (based on 3,500 kWh consumption per year) [51, 52] and 0.335 €/kWh in the first half of 2022 [53]. This suggests, that the model of prosumers has to be analysed "by embedded market elements as well as possible operation and service layers" [54], which means in fact to consider the positive and negative balancing market in the model. Balancing power, traded on the balancing market, is needed to keep the grid stable by guaranteeing equal levels of injection and extraction at any time.

With the model of prosumerism, self-sufficiency comes into focus [55]. Also the use of smart controlling elements can increase the self-sufficiency rate of households [56]. However, behavioural studies have shown, that customers not always react economically rational, which means customers not necessarily choose financial benefits over others, such as autarchy [57–59]. To stick with measurable financial settings, behavioural elements as well as smart consumption is not considered in this paper. Hence, this paper focuses on the need to evaluate the financial perspective coming with the change from a centralized top down market towards a decentralized bottom-up model (see also [60]).

The concepts of prosumers, micro-grids or virtual power plants (VPPs) have already been objects of research. Specifically, the concept of smart generation and consumption, which means, that an algorithm-based demand management is used for optimization, has become a prominent research topic [13, 61, 62]. Lund et al. (2014) [61] found that smart thermal and smart electricity grids complement each other. Furthermore, both systems are needed for the implementation of sustainable energy systems [61]. Others [25–27] analysed models with the focus on prosumers working with PV systems and battery storages. While Moshövel et al. (2015) [27] show that grid management within the Energy Community has a higher impact than maximizing the individual self-consumption, they emphasize the importance of relieving the load on the grid. In this vein, Lorenzi and Silva (2016) suggest to invest in batteries that allow to respond to demand changes and would therefore reduce necessities to manage the grid [26]. Quoilin et al. (2016) [25] inter alia point out that self-consumption is a non-linear, almost asymptotic function of PV and battery sizes.

Others, like Quoilin et al. (2016) or De Coninck et al. (2014) [25, 63] analysed micro-grids, which operate part-time in island mode and, in case of De Coninck et al. (2014) [63], did not only consider electrical energy but also heating and hot water. The results show that thermal energy storage seems to be very promising [63]. However, Barbour et al. (2018) [29] studied a local micro-grid in the UK, with the result that micro-grids increase the self-sufficiency rate, but also that barriers for the electricity exchange have to be decreased for micro-grids. The last point comes especially into play when smart infrastructure controls the energy exchange, as Grijalva et. al. (2011) [54] and Luo et. al. (2014) [21] analysed in the context of a prosumer-to-prosumer exchange and show that the proposed energy trading can increase the utilization of renewable energy and reduce costs of energy purchase and energy storage. Lorenzi and Silva (2016) [26] employed an optimization algorithm to study the feasibility and profitability of a micro-grid system, while Chabaud et al. (2016) [64] use a similar approach for a household with two adults and two children. In a more comprehensive way, Moshövel et al. (2015) [27] investigated different management strategies of PV and/or battery driven households in terms of self-sufficiency.

Putting all these studies in a nutshell, higher energy prices and decreasing investment costs for PV panels and battery solutions are moving prosumerism further into focus. Although, solutions for individual households seem to be already beneficial, Energy Communities promise to be even more efficient in the fields of reliability and financial performance. Therefore, different requirements, such as battery compatibility for demand response, should be met and various strategies can be chosen to implement an Energy Community, as described in section 4.2.2 and can be seen in Figure 48.

In general, the results imply that further analysis is needed in terms of energy generation, storage and consumption within Energy Communities in the housing sector [29, 49]. This is particularly important as the housing sector causes about one third of the total energy demand [65].

Of course, it is clear that such Energy Communities are difficult to establish, as they ultimately entail a (further) paradigm shift in the energy system. As a minimum, they must be financially attractive. Moreover, such changes of the infrastructure's use and new responsibilities, as well as new opportunities in terms of managing electricity and data demand require new governance regulations [43]. Market barriers and political barriers in production and distribution have to be adapted accordingly [41].

Taking these fundamental changes in mind, the energy sector faces a disruptive change. It will be not only technical processes that bring the European energy system forward using, for instance, sensors, storage, remote control and automation systems, but also modernized management structures to properly control these techniques [40].

In summary, the review of already existing models and literature shows the need for a decentralized and community-based energy supply to accelerate the energy transition process on a general level and to create economic benefits for the Energy Communities. Since many variables can play a role and technical feasibility as well as market regulations are strong barriers, the design of these communities is crucial for the economic feasibility of this concept.

4.2.2 Micro-Grids and Virtual Power Plants (VPPs)

The distinction between micro-grids and virtual power plants (VPPs) depends on the circumstances assumed. In general community-based energy generation and consumption are based on the idea of decentralization and findings about that point out benefits for such systems [66]. Prosumers usually build the basis for micro-grids and VPPs, which not only consume energy but also produce it. The interaction of prosumers to redistribute energy in a grid is usually seen as a micro-grid [67]. Prosumers follow economic motivations and may operate assets like energy generation units, storage utilities and an electric grid [68]. Especially the last point makes it hard to distinguish between prosumers and micro-grids. Some authors even define one prosumer household with heat and water management as a micro-grid [63]. The distinction between micro-grids and VPPs can be made, for instance, by the aim of the community. Micro-grids usually are communities of locality, while VPPs usually are communities of interest [69]. However, market forms with local prosumers usually are in immediate vicinity and pursue economic goals. One example is the first cooperatively owned wind farm in the UK [70] where people of a community bought shares to finance the project, but also to realise economic profits [69]. These associations can be managed by community charities that provide local services [71]. The markets, where such communities operate, are different from existing systems because users do not only react to price signals, but can also provide services that electric utilities, system operators or other prosumers have to bid for [67].

Hence, such Energy Communities, consisting mainly of prosumers in the same local area, can be seen as micro-grids with an economic purpose. While VPPs also have an economic purpose, they do not necessarily need to be in the same geographical area. In the following the term Energy Community will be used for a local community which generates and demands electricity, provides storage capacities and pursues economic goals.

Studies underline that such concepts with active roles of the participants are in demand [66, 69] but also require actions to make Energy Communities attractive [66]. On the other hand, Energy Communities can be part of a flipped market model where electricity generation mainly happens on a low voltage level. The distribution and the management of such bundles of Energy Communities technically can take various forms. The following Figure 48 shows the main models discussed in the literature summarized by Parag and Sovacool (2016) [67].

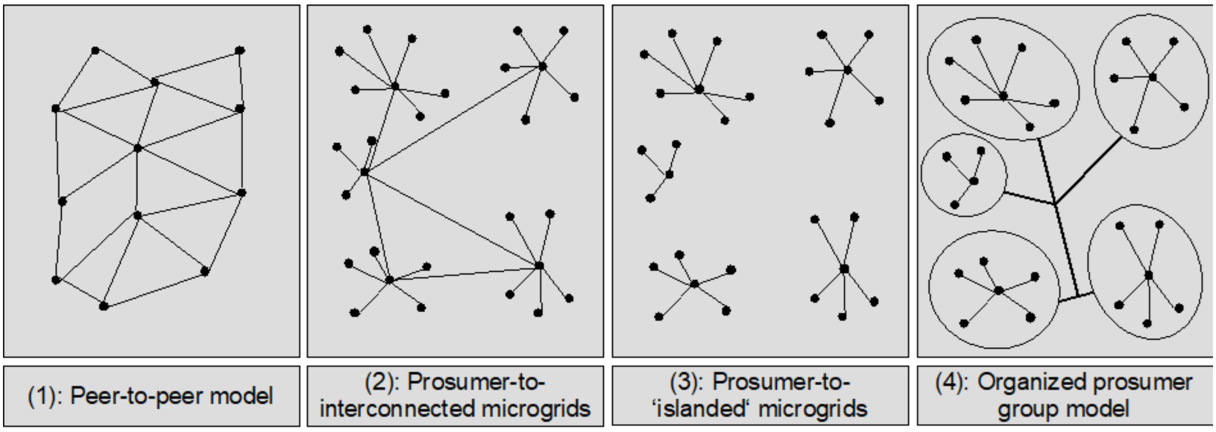

Figure 48: Structural attributes of Energy Communities [67]

In the peer-to-peer model (1) prosumers are directly interconnected and can exchange energy and services among each other. While in the prosumer-to-interconnected model (2), microgrids bundle prosumers in micro-grids. These micro-grids are interconnected on low voltage basis to provide services from micro-grid to micro-grid. In contrast, prosumer-to-'islanded' micro-grids (3) assume that all microgrids run autonomously. The organized prosumer group model (4), where prosumers pool their resources [67], represents the idea of Energy Communities in this simulation the most. Here, prosumers are interconnected in Energy Communities, which are clustered and can be calculated as separate groups. These are connected to the superior grid to exchange services and additional power. Within a system of multiple Energy Communities, these communities are able to provide services to its members and to the superior grid, which finally can be the connection between numerous Energy Communities.

This paper focuses on one Energy Community and its interaction with the grid at today's market conditions and prices to analyse the financial profitability of local energy generation and consumption. This setting has been coined as zero Energy Community [72]. The definition expresses the idea that renewably generated electricity is fed-in the grid and can be demanded with delay, so overall the energy balance of the grid connection point is zero [72] – or in best case, the Energy Community provides electricity to the public grid. Although this is theoretical accounting, Energy Communities can have an impact on reducing CO_2 emissions by using local and renewable electricity first. It can be also assumed that the power grid will be increasingly supplied by electricity generated from RES, which requires other technical settings, incentives and also market structures in the future.

4.2.3 Regulatory Framework

Over the last decades, the German government has introduced multiple incentives and regulations invested in electricity generation from renewable. Because these incentives rely, for instance, on the size of the generation systems and various other factors, some incentive systems have an impact on today’s situation and the economic feasibility of Energy Communities. Others refer only to renewable generation but not to Energy Communities.

The costs for incentive measures are mainly allocated to private customers via the energy price. These allocations can be taxes, such as VAT, or specific-purpose surcharges, such as allocations from Energy Conservation Act (EEG-Levy), which subsidize the gap between market revenue and guaranteed payments per feed-in energy by renewables. Figure 49 shows the structure of electricity pricing for households in Germany in 2022.

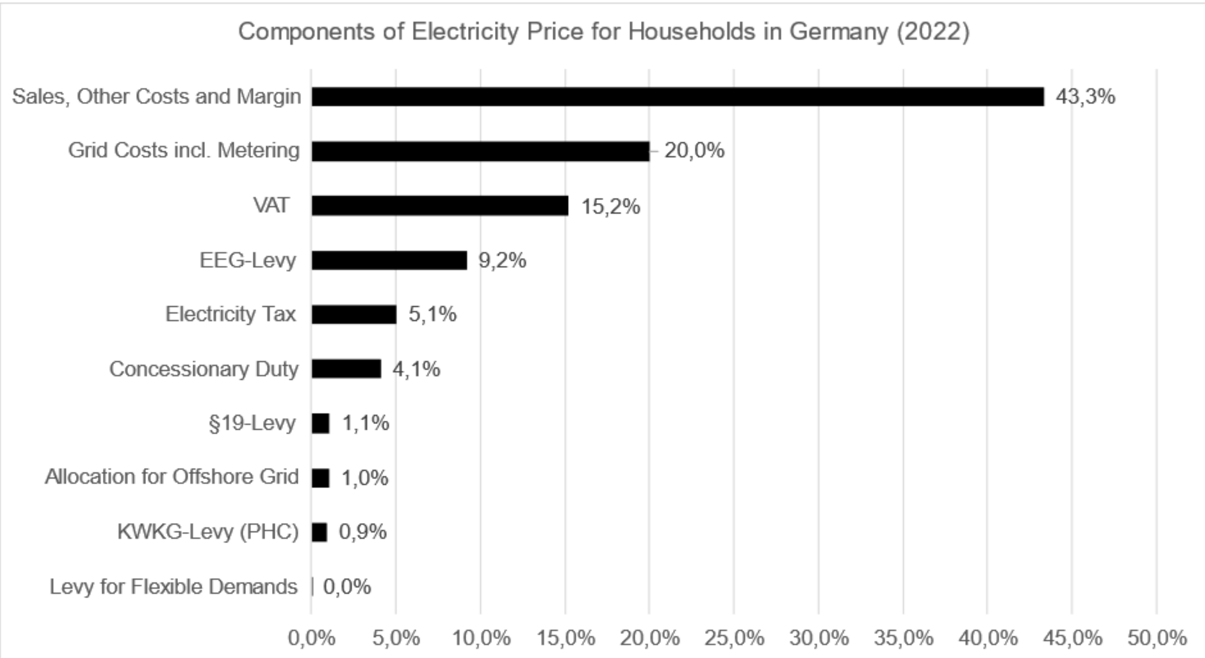

Figure 49: Composition of the electricity price for households in Germany in 2022 [73]

Power heat coupling (PHC) is subsidised via the Kraft-Wärme-Kopplungsgesetz (KWKG), which is financed by the KWKG-Levy. §19-Levy is paid by most of the customers and cross finances discounts in grid costs for only few customers. It is striking that EEG levy and grid costs together are responsible for almost one third of the electricity price. Due to regulations, the EEG levy increased by 331% since from 2010 to 2020 as it is shown in Figure 50 [74, 75] and has been reduced in 2021 and 2022 because of new political regulations [73, 76]. Beginning in January 2023, the EEG-levy will be financed entirely by federal funds [77]. The grid costs for private households increased from 6.34 ct/kWh to 8.12 ct/kWh from 2007 to 2022, as shown in Figure 51 [73–75]. Figure 52 shows the combined additional costs for private households due to grid costs and EEG levy. It can be seen that these costs have a substantial and rising impact on the electricity price and are only starting to decrease because of the political regulations due to the EEG-levy.

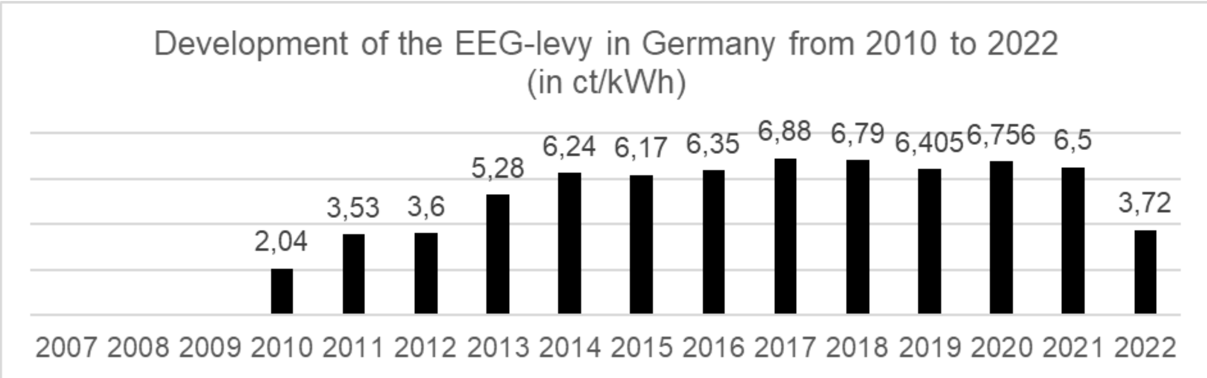

Figure 50: Development of the EEG-levy in Germany [73–76]

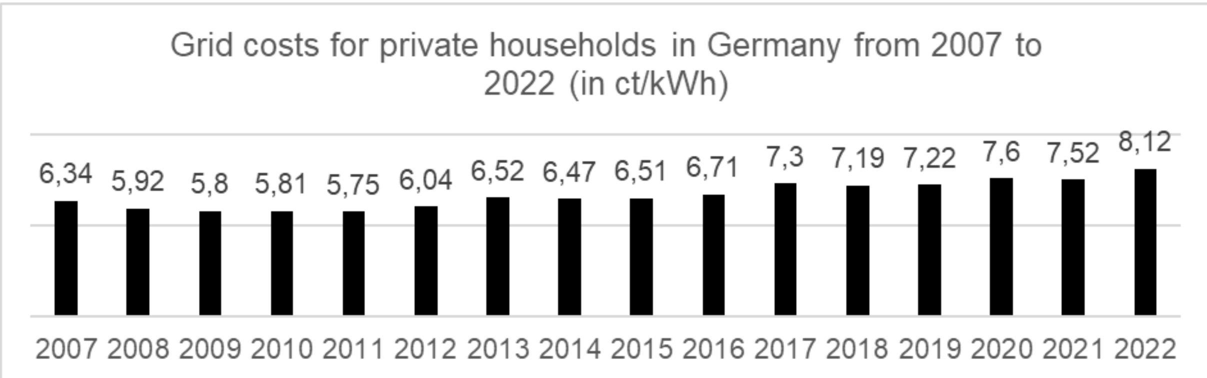

Figure 51: Grid costs for private households in Germany [73, 75, 76, 78, 79]

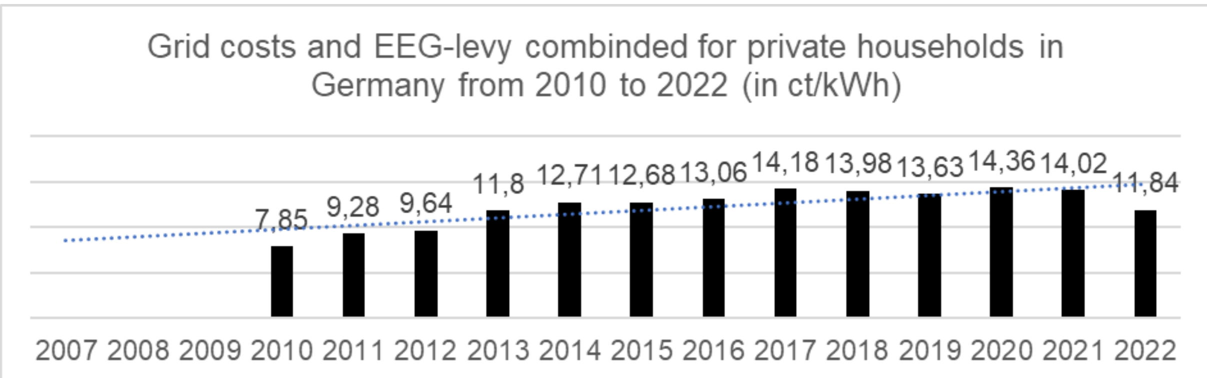

Figure 52: Additional costs for private households due to grid costs and EEG levy [73–76, 78]

Assuming that Energy Communities can renounce to pay grid costs and levies for self-consumed and self-generated electricity, the saving potential for households seems to be enormous.

For this purpose, the regulators in Germany already have models, next to the fixed remuneration for small PV systems up to 10 kWp, for different scenarios which generate and consume electricity renewably [80]. The following three examples

- Electricity-model for tenants,
- 750 kW limit for generation and
- Regulations for participation on the balancing market

will be introduced and discussed in the next sections.

Electricity model for tenants

In the electricity model for tenants, the electricity is generated either with a combined heat and power plant, or a PV system on the top of a residential building to provide electricity to end customers (the tenants) [81]. The EEG levy is incurred for every kWh consumed by the end customer and has to be paid by the end customer. Unconsumed electricity can be fed into the public grid or stored locally [81, 82]. In general, the model can be described as in Figure 53.

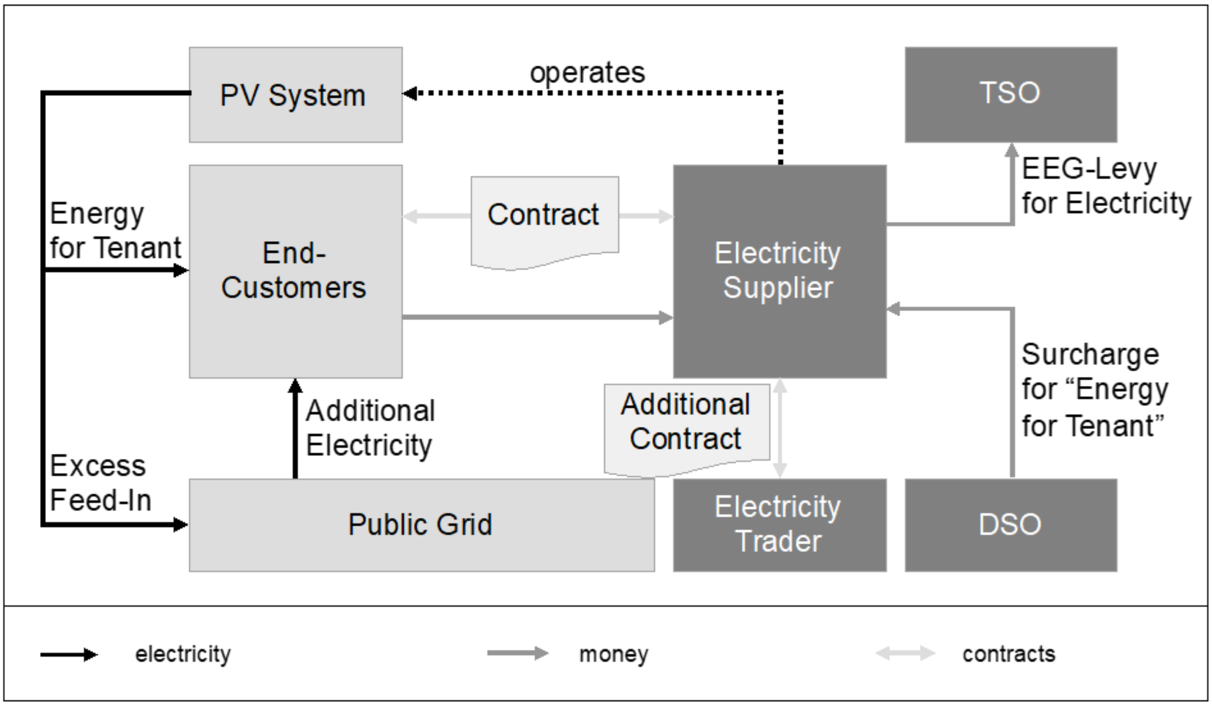

Figure 53: Electricity model for tenants [83]

The model shows that the electricity supplier, which is also the landlord, has contracts with end customers as well as with traders to cover demand not matched by the local community. In reality, the landlord often may not generate or supply the electricity, but uses third parties for this purpose [81]. For tenants the electricity is often cheaper, because some costs are not relevant, like grid costs, electricity tax or concessionary duty, while EEG levy still has to be paid [81, 82]. This concept is also used as a template for one of the later scenarios.

The model also has some restrictions. For instance, the maximum size of a PV system is 100 kWp [84]. Similar to privately owned and used PV systems, there are no grid costs for electricity directly used by the tenants from the PV system on the roof of an apartment building [82]. Furthermore the used electricity is also exempted from electricity tax as long as the generation system is below 2 MW nominal power [82].

The rentability of such a model highly depends on the number of end consumers [81]. Because the financial advantages to both tenants and landlords are often not specified, but the model is an important lever for meeting the governmental annual target for additional PV installations, another more appropriate model is often requested [81].

This paper is calculating a model, based on an idea similar to the electricity model for tenants, and considering the current market conditions. This study evaluates the need of changes in the regulatory and political framework to meet the objectives of an enlarged market environment.

750 kW limit for generation

Renewable energy generation systems above the size of 750 kW need to participate in the bids on the electricity exchange, hence they have to participate in the electricity market [85, 86]. Furthermore, newly installed renewable generators have to compete in the application process concerning economic efficiency in operations [80, 87]. As a result, only the most efficient projects reach the realization phase. But some market mechanisms are working even for PV systems above the nominal power of 100 kWp since January 1st, 2016 [88]. Such systems have to participate in the electricity exchange too, as they get compensated by law if the selling price is lower than the fixed price guaranteed for small PV systems [89]. In practice, distribution system operators (DSOs) usually facilitate of the trading and compensations [90].

For this compensation the EEG levy is used. As described, the EEG levy is part of the electricity pricing and all end customers have to pay it, even if self-generated electricity is used [80]. From 2023 EEG levy will be not part of the electricity price anymore but financed by taxes [77]. As Figure 50 shows, the EEG levy is not only stagnating or even slightly increasing over the last years, but also in practice the revenues from EEG levies of renewable systems often exceed the revenues from electricity selling [90]. For this reason, to lower the energy price for all, this paper calculates a subsidy-free model, which revenues are generated through participation in the electricity and balancing markets.

Regulations for participation on the balancing market

Well-managed electricity grids always balance generation and consumption of electricity. Differences between generation and consumption have to be compensated by balancing power for keeping the grid stabile [91]. Therefore, balancing power describes the electricity and capacity needed to cover power fluctuations within the grid. For securing such balancing power transmission system operators (TSOs) are responsible in their regulation area, which is the region where TSOs operate as monopolist. So-called System Services for grid stabilization are part of, inter alia, secondary control as well as tertiary control systems [91]. Secondary control balances the grid within the balancing area for electricity excess or shortfall for 30 seconds to five minutes after the frequency deviates from 50 Hertz by +/- 0.1 Hertz or more. Tertiary control, similar to secondary control, balances power from five minutes after the incident up to 60 minutes. Energy Communities can offer system services, which on the one hand stabilize the grid and on the other hand lead to additional revenues.

In the future, system services are expected to be increasingly provided by renewable energy generators instead of conventional power plants. For this purpose, the bid conditions for participating at the electricity exchange are customized towards the needs of wind turbines and PV systems. However, the needs of controlled consumption systems and electricity storages are also considered in these changes [91].

The changes affect the bid conditions for secondary control by changing the weekly bid into a daily event and shorten the period of service provision to four hours, which is an important issue for volatile generators, like wind turbines and PV systems. In terms of harmonization, the same requirements are introduced for tertiary control too, which generates synergies for the providers of balancing power [91]. Furthermore, secondary and tertiary control are also allowed to be offered not only in their area of responsibility for balancing, but also beyond of the regulatory requirements [91].

The introduced model in this paper also profits from changes regarding the needed minimum size of systems which are allowed to offer balancing power. To support the participation of small and medium sized systems, the minimum size was lowered from 5 MW nominal power to 1 MW nominal power [92, 93]. This affects not only the sizes of generation units, like PV-systems, but also the dimensioning of storage units, like batteries. The introduced model takes advantage of these changes to simulate the participation in the markets for secondary and tertiary control.

4.3 Modelling

Given the situation of the German energy market and the need for new business opportunities to promote renewable electricity generation, this paper develops a new market model for Energy Communities. Central market settings are considered to set up a most realistic model, which allows to change influential factors to receive answers on the research question and to determine which factors should be changed in order to reduce the need for subsidies and making the idea of decentralized electricity generation and consumption more financially attractive.

4.3.1 Optimization of the Simulation Model

To evaluate the research question properly, different methods seem to be appropriate. In a first step, a way has to be found to build a model which reflects the reality as best as possible to analyse the financial advantageousness of an Energy Community. Since the research question does not include the way end-customers consume electricity and no smart solutions of energy consumption are object of consideration, this study is less a social study, and more a technical one analysing the market scheme.

There are also studies, which analyse the break-even price of energy (BEPE) of renewable energy projects, which consider specific aspects of the legal and financial framework [94]. The break-even point reflects where revenues are equal to the costs caused by the production of a good or service [95]. Since revenues and costs clearly depend on many factors of the Energy Community, it does not seem to be trivial to calculate them. Furthermore, different assumptions can lead to different results, which are difficult to compare [94].

Taking into account the assumptions made we focus on net cash flow generated by the Energy Community, which is part of the net present value (NPV)

$$NPV = \sum_{t=0}^{m} \frac{NCF_t}{(1+r)^t}$$

where NPV reflects the discounted cash flows for *m* years, NCF is the net cash flow generated by the Energy Community for the years $t = 1,\ldots,m,$ and r is the discount rate [96, 97]. To calculate the overall NCF of the Energy Community, a simulation of all cash flows has to be carried out. The overview of the input factors is given in Figure 54. Note that the model includes a multitude of variables and factors, which are set by regulations, laws or the market of electricity. It is one of the most important contributions of the simulation in this paper to align these factors and connect them in a way to simulate the cash flows of an Energy Community in a most realistic way with the opportunity to analyse the impacts of each factor. In the model, the net present value reflects the sum of all discounted NCF. The NCF includes all relevant cash flows of the modelled Energy Community as a service, taking into account the usage fees for the non-owned generation and storage assets. The investment in generation and storage assets is fully covered by the usage fees over the period of consideration. The simulation combines the regulatory conditions and the functions, described in the following, for maximizing the NPV. Figure 54 provides an overview how given subfactors are merged to factors in the different categories of the target function.

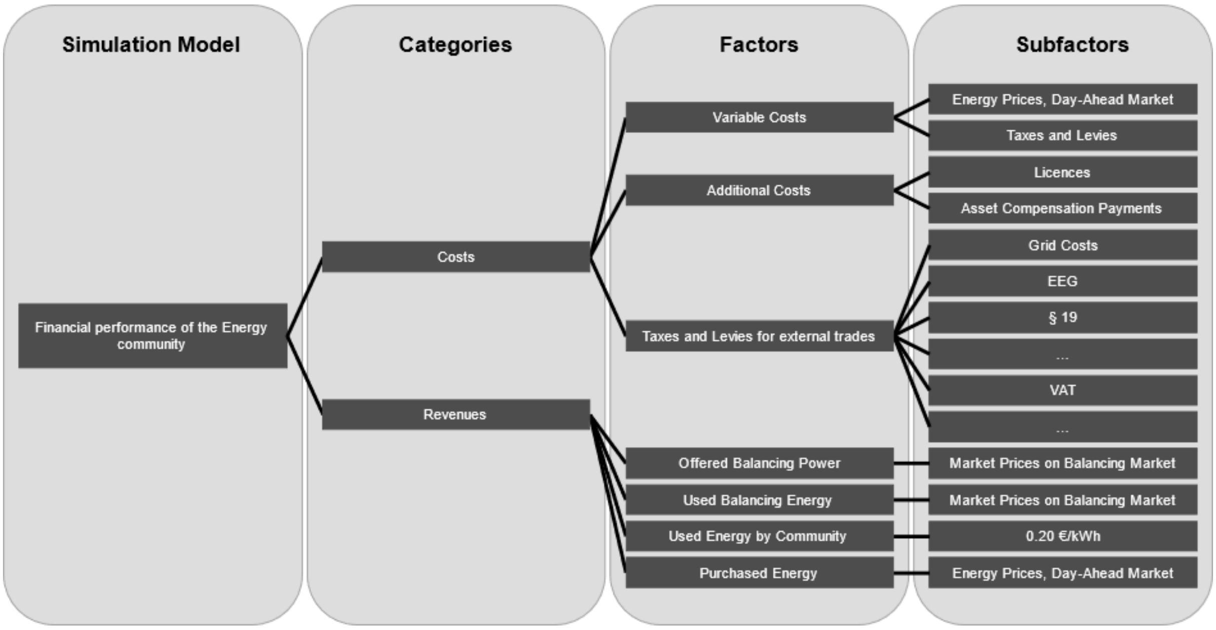

Figure 54: Overview of input factors to NCF

To analyse the model in terms of the research question the NPV is maximized which leads to the following objective function:

$$Max\ [\left(\sum_{t=1}^{n} R_t\right) - \left(\sum_{t=1}^{n} C_t\right)]$$

with

$$R_t = R_{DA} + R_{SN} + R_{SP} + R_{TN} + R_{TP} + R_{CP}$$

and

$$C_t = C_{BES} + C_{PV} + C_L + C_T + C_P + C_{AL}$$

Thereby the different factors are set as described in Table 22.

Variable	Explanation	Calculation
R_t	Revenues in year t	
R_{DA}	Revenues from Day-Ahead Trading	$\sum_{t=1}^{n}(SE_{DA\,t} \times WP_{DA\,t})$
R_{SN}	Revenues from negative Secondary-Control Market	$\sum_{t=1}^{n}(DE_{SP\,t} \times WP_{SN\,t} + AK_{SN\,t} \times PP_{SN\,t})$
R_{SP}	Revenues from positive Secondary-Control Market	$\sum_{t=1}^{n}(SE_{SP\,t} \times WP_{SP\,t} + AE_{SP\,t} \times PP_{SP\,t})$
R_{TN}	Revenues from negative Tertiary-Control Market	$\sum_{t=1}^{n}(DE_{TP\,t} \times WP_{TN\,t} + AK_{TN\,t} \times PP_{TN\,t})$
R_{TP}	Revenues from positive Tertiary-Control Market	$\sum_{t=1}^{n}(SE_{TP\,t} \times WP_{TP\,t} + AE_{TP\,t} \times PP_{TP\,t})$
R_{CP}	Revenues per consumed energy	$CE \times FEP$
C_t	Costs in year t	
C_{BES}	Linear Usage Fees of BES-System	$\frac{INV_{BES}}{D}$
C_{PV}	Linear Usage Fees of PV-System	$\frac{INV_{PV}}{D}$
C_L	Costs for balancing power	$\sum_{t=1}^{n}(SE_t \times BP \times C_{BP} \times VAT)$
C_T	Tax (VAT)	$\sum_{t=1}^{n}(SE_t \times VAT)$
C_P	Costs for trading licences	Fixed value
C_{AL}	Additional levies in German market system	$\sum_{t=1}^{n}(DE_t \times \left(\sum_{j=1}^{8} C_{AL\,j}\right))$

Table 22: Description of optimization factors

AE	Available Energy	D	Duration for Depreciation
AK	Available Capacity	DE	Demanded Energy
BP	Share of balancing power	FEF	Fixed Energy Fee
C_{AL1}	§19-Levy	FEP	Fixed energy price
C_{AL2}	Levy for flexible demands	INV	Investment
C_{AL3}	KWKG-Levy (CHP)	INV_{BES}	Investment for BES-System
C_{AL4}	Other costs	INV_{PV}	Investment for PV-System
C_{AL5}	EEG-Levy	n	Number of trading time slots
C_{AL6}	Electricity tax	PP	Power Price
C_{AL7}	Grid costs	SE	Sold Energy
C_{BP}	Costs for balancing power	VAT	Value-added tax
CE	Consumed Energy	WP	Energy Price
C_P	Costs for trading licenses		

Table 23: Abbreviations of factors

The simulation model does not only reflect factors based on regulations but can also include the variation of different electricity prices for end-consumers as well as compensation payments for investment costs caused by the procurement of assets like PV systems and storage units such as batteries, since the model of an Energy Community is created as a service, respecting usage fees of any generation or storage assets.

The identification and comprehensive simulation of all relevant factors is a major outcome of this paper, which allows to identify market potentials as well as the opportunity to present political implications towards a further harmonization of the electricity market in favour of decentralized and renewable generation.

4.3.2 Simulation Model

The simulation model used is based on real data of the solar radiation in the German city of Aachen. Furthermore, the H0 consumption curve for households given by the regional DSO is used to model the consumption of households. The H0 curve, also standard load profile, is a representative load profile over the average of a consumer group, in this case for private households. Since regionality of the simulated Energy Community is key, these are essential starting points. Next, the Energy Community reflects a group of prosumers, which can also provide electricity for themselves. Following the objective function, the model considers real data regarding all relevant cash flows. This includes costs in conjunction with renewably generated electricity and constructs for exchanging energy within the community and with external partners as introduced in section 4.2.3. Figure 55 illustrate the model structure by Breyer et al. [98], that also builds the basis for the simulations in this paper.

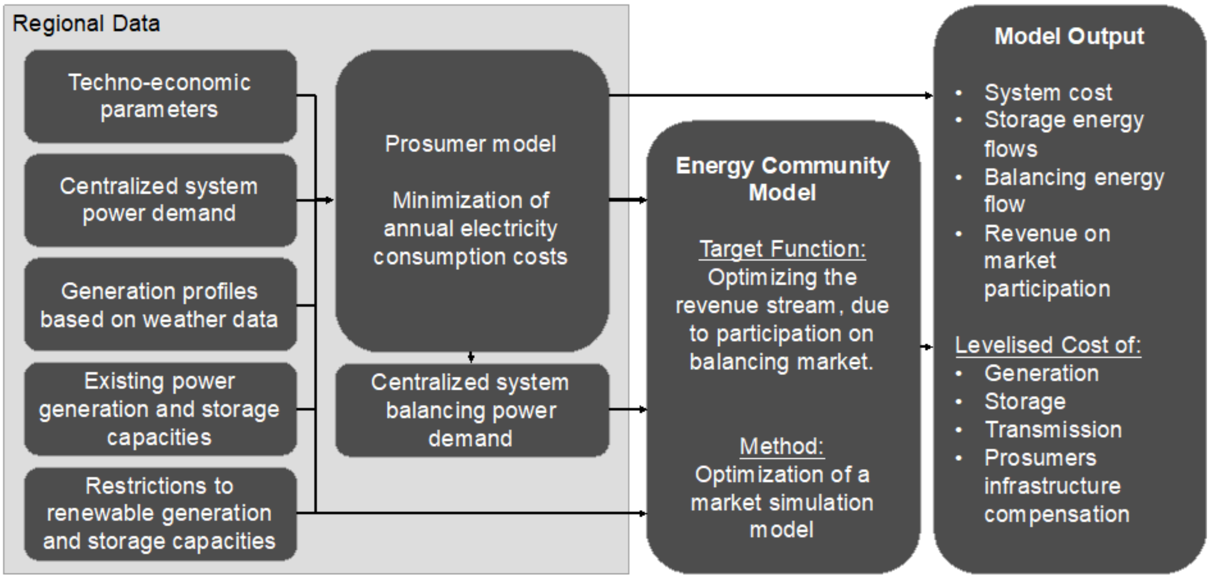

Figure 55: General model for simulation following Breyer et al. [98]

To calculate the NCF, the period under consideration is assumed as one year, but a variation of input data sets guarantees the validity of the results. For example, for global solar radiation the data sets range from 2013 to 2017. In addition, market data sets from different years are used for testing the model.

The simulation model contains various variables which can be customized. For the generation of electricity, not only the data set for the solar radiation can be modified, but also the total size of the combined PV systems can be adjusted. The total size of the battery storage system can be varied.

Besides taxes and levies, the following types of cash flows are included:

<u>Compensation of internal losses</u> is considered with a factor based on the consumed electricity and can be charged with typical costs of 0.03 ct/kWh [82, 86] for balancing power. The calculation is based on the assumption that 10 % of exchanged electricity within the Energy Community is needed for balancing power, due to losses in electronic components and losses of the grid [99]. Hence, this energy is charged with the price of balancing power and respected in the calculation.

<u>Payments for trading licences</u> are considered as a fixed price per year and contain costs for licences for needed software tools, and the licence to trade on day-ahead markets and balancing markets.

<u>Compensation for generation and storage systems</u> cover payments to the prosumers (individual households) for letting the Energy Community use their assets such as battery storage or a PV

system. In fact, the prosumer of the Energy Community buys the assets and gets compensated by usage fees, which reflect the discounted cash flows of the provided asset over the period of consideration, generally 20 years. It also can be stated that these payments of usage fees are opportunity revenues for the prosumers, since they do not face any other costs or pricing risks. However, these usage fees are included in the calculation of the Energy Communities' Cash Flow and represent the fact of internalizing asset costs within the business model.

Also, the revenue structure of the Energy Community is based on different factors, which are integrated in interdependent decision-making rules: First of all, energy demand of the Energy Community is satisfied by self-generated electricity if possible. If there is no sufficient supply, electricity is demanded on the day-ahead market. In case of surplus supply, electricity can be sold at the day-ahead market.

Furthermore, if the capacity of the combined storage systems exceeds one MW, the participation in the balancing market is forced by bidding on the power price. Regardless of winning the bid, the lowest power price is considered as revenue for the Energy Community in terms as prudence principle, which means with different financial options always the most disadvantageous option is chosen in the model to ensure conservative results of the model. If the energy price of the balance power is lower than the energy price at the day-ahead market, the Energy Community wins the bid and adds the amount of electricity to the model as well as the revenue of the energy price. Again, the lowest agreed price is considered, again following the prudence principle. This approach is the same for both considered balancing markets, secondary and tertiary. The power price determines which market is chosen in the simulation, the day ahead market or the balancing market.

Bids for available energy are structured similar as bids on the balancing market in the case of available capacity. If the available stored power exceeds one MW, the participation in the balancing market is forced by bidding on the power price. Again, the lowest price is chosen as revenue. If the price for balancing energy is lower than the price for energy on the day-ahead market or even is negative, the Energy Community gets the bid. Similar to the participation rules on positive balancing markets, the decision-making rule indicates bids on the balancing market which is financially more advantageous for the Energy Community. This procedure guarantees the best financial strategy, but with a maximum of caution to reflect a conservative business model.

Since the model assumes so far, that every participant of the Energy Community receives electricity for free, an additional revenue stream is introduced, to minimize counterproductive behaviour, as it could result from not saving energy due to free electricity. Consequently, the Energy Community charges a fixed price per kWh for consumed electricity, which results in positive cash flows for the Energy Community as a business unit.

4.3.3 Assumptions and Used Data

As already described, the analysed Energy Community is composed by several prosumer households. All these prosumers are considered to have the same conditions, which is a PV system, a storage system and an average consumption profile based on the H0 profile. Hence, a variation of the households participating in the Energy Community indicates a variation of the total sizes of the respective generation and storage systems as well as a variation in total consumption. Assuming a size of 10 kWp of each PV system and a size of 10 kWh of each storage system, at least 100 households in Energy Community are needed in an Energy Community to be permitted to trade on the balancing markets, according to the One MW restriction.

While Figure 55 shows the general structure of the established simulation model, Figure 56 illustrates the model of the Energy Community and how the grid connection point is placed in this simulation model. Furthermore, the graphic also shows how the Energy Community is connected to the market system via the grid connection points.

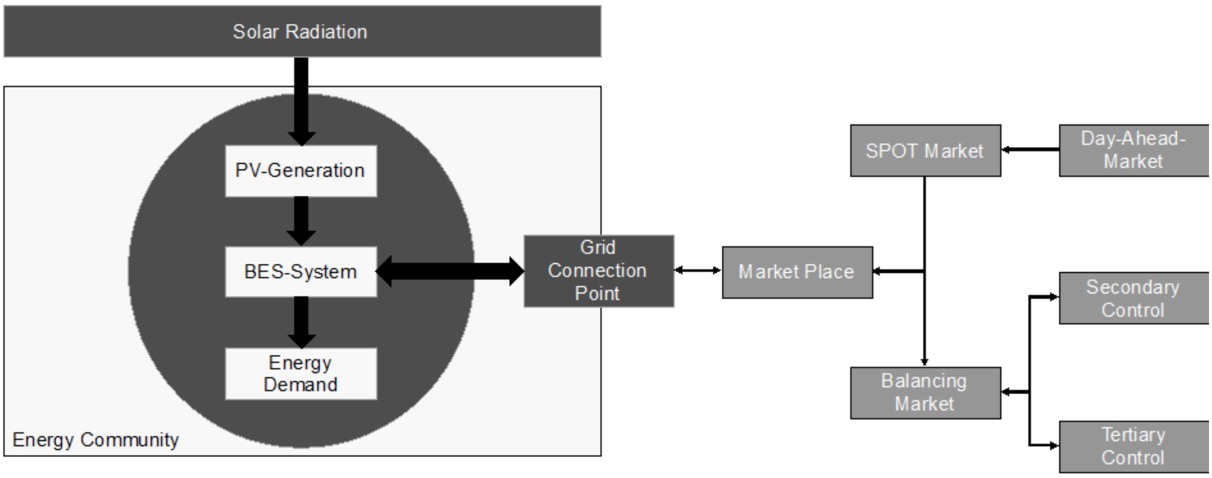

Figure 56: Model of the Energy Community

As is can be seen, the spot market and the balancing market are organized in different structures. The data used for these markets are given by the German federal network agency and reflect real data to model the decision making process for the Energy Community [100].

Furthermore, a number of variables is used in the simulation model, as shown in Table 24.

n	2190	Number of trading time slots	365 days per year, trading slot is 4 hours
r	0,6 %	Used interest rate in the model	[101]
CE	3.500 kWh	Consumed energy per household	[82]
FEP	0.2 ct./kWh	Fixed energy price	Assumed in the model
INV_{BES}	1,250 €/kWh	Investment for BES-System	[49, 102]
INV_{PV}	1,167 €/kWp	Investment for PV-System	[49, 103]
D	20 a	Duration for Depreciation	[104–108]
BP	0.1	Share of balancing power	[82, 86]
C_{BP}	0.03 ct/kWh	Costs for balancing power	[82, 86]
VAT	0.19	Value-added tax	[82, 86]
C_{P}	21,600 €	Costs for trading licenses	[82, 86]
C_{AL1}	0.0305 ct/kWh	§19-Levy	[82, 86]
C_{AL2}	0.005 ct/kWh	Levy for flexible demands	[82, 86]
C_{AL3}	0.28 ct/kWh	KWKG-Levy (CHP)	[82, 86]
C_{AL4}	0.416 ct/kWh	Other costs	[82, 86]
C_{AL5}	6.405 ct/kWh	EEG-Levy	[82, 86]
C_{AL6}	2.05 ct/kWh	Electricity tax	[82, 86]
C_{AL7}	4.62 ct/kWh	Grid costs	[82, 86]
C_{AL8}	1.99 ct/kWh	Concessionary Duty	[82, 86]

Table 24: Variables used in the simulation model

The used numbers are mainly determined by regulations and by law [82, 86]. Numbers without such values reflect commonly used values. For instance, it is assumed that the electricity consumption per household is 3,500 kWh per year [82]. Also, investment costs for the PV and storage systems are based on typical values such as 1,167 Euro per kWp for PV systems [49, 102] and 1,250 Euro per kWh for battery storage systems [49, 103]. The depreciation is set with twenty years for both, PV and storage systems [104–108]. Finally, the fixed energy price (FEP) assumed to be paid per kWh by the end-consumers of the Energy Community is set to 0.20 Euro per kWh. This price is lower as the average electricity price in Germany [109] and presumably high enough to achieve a steering effect not to counteract the energy efficiency.

4.4 Scenario Analysis

For the described simulation model, a scenario analysis has been carried out to validate the impact of different variables on the financial performance of an Energy Community trading on the balancing market in Germany. There are several basic assumptions. As described, it is assumed, that each household provides a 10 kWp PV system and a 10 kWh battery system. Furthermore, every household is assumed to consume 3,500 kWh electric energy per year. The solar radiation is based on the average value for the five years from 2013 to 2017.

Previous studies have shown that a similar setting results in an annuity of the net present value of -1,169.87 Euro for each household, if it is not participating in the Energy Community but has to rely on the fixed remuneration system via subsidies for private households [49]. Even if the results of the NPV of the former studies and the NCF in this study are not completely comparable, the results set a baseline for the financial added value that can be provided by Energy Communities.

Three different scenarios are evaluated. The settings vary and start from the smallest possible number of households in an Energy Community to meet the target of at least one MW system size, which is 100 households, in an Energy Community. The two other cases reflect Energy Communities of 150 households and 200 households respectively, as depicted in Table 25. These settings reflect the basic assumptions on consumption, generation and battery storage described above. The size of the cases starts with a generation potential of 1 MW which reflects 100 households with a 10 kW_p PV system each (Case 1). This means with a battery size of 10 kWh per household, the Energy Community needs to have a minimum of 100 households to be allowed to participate in the balancing markets. Case 2 represents 150 households, case 3 200 households to size the physical structure within realistic limits but also to show the disproportionality as size increases. Furthermore, a bigger number of households within the Energy Community could possibly lead to practical challenges, for instance requires a larger grid infrastructure, which needs to be balanced, even though it is theoretically possible. One power box to control the distribution of electricity to houses is located every 700m on average [110]. For instance, power boxes can be seen as technical controlling points of an Energy Community and therefore limit the number of participating households by the space needed to install PV systems having in mind the average size of a private property [111]. Nevertheless, those three cases on the one hand show the potentials of Energy Communities with growing sizes of generation units, storage units as well as consumption. On the other hand, it can be seen the financial benefits of an Energy Community do not grow linearly with the growth of the Energy Community's size.

	per household	Case 1	Case 2	Case 3
Consumption [kWh]	3,500	350,000	525,000	700,000
PV System [kW_p]	10	1,000	1,500	2,000
Battery System [kWh]	10	1,000	1,500	2,000

Table 25: Cases for scenario analysis

Each case analysed is also subdivided in three variations (A, B and C). Variation A considers the Energy Community as a comprehensive business model with all restrictions as well as taxes and levies. Variation B excludes VAT and levies (see chapter 4.2.3), such as grid costs for electricity exchanged in the Energy Community. This is the case respecting current legislation for other constructs as described in chapter 4.2.3. It is assumed in this variation, that the market simplifications are also applicable on the Energy Community. The third variation C, the business model with all restrictions, includes taxes and levies but excludes any battery storage. This variation is created to exclude the high initial costs for battery storage and to see how storage influences the market participation of the Energy Community. For all variations (A, B, and C) the remunerations of the Energy Community are calculated considering

i. No compensation for PV and battery systems, no trading license costs and no consideration of balancing power.
ii. With all costs and losses considered, but free electricity to the members of the Energy Community.
iii. With all costs and losses considered, plus 0.20 Euro/kWh FEP per kWh consumed in the Energy Community.

Figure 57 visualizes the variations of all 27 calculated scenarios, while variation A represents the current market situation in Germany and specification ii. or iii. the most realistic business case, depending on the decision if consumption is for free or not. This is also visualized in Figure 58.

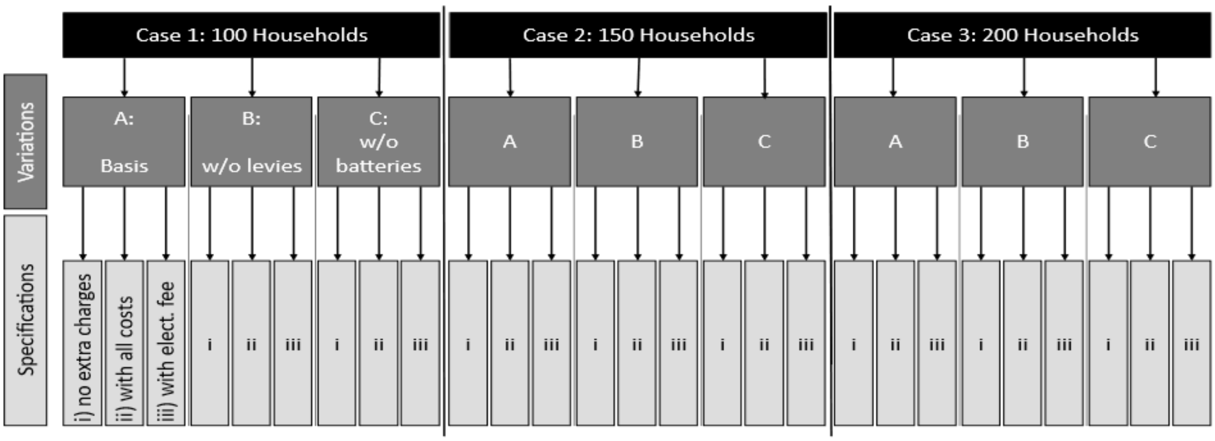

Figure 57: Variations of the calculated scenarios

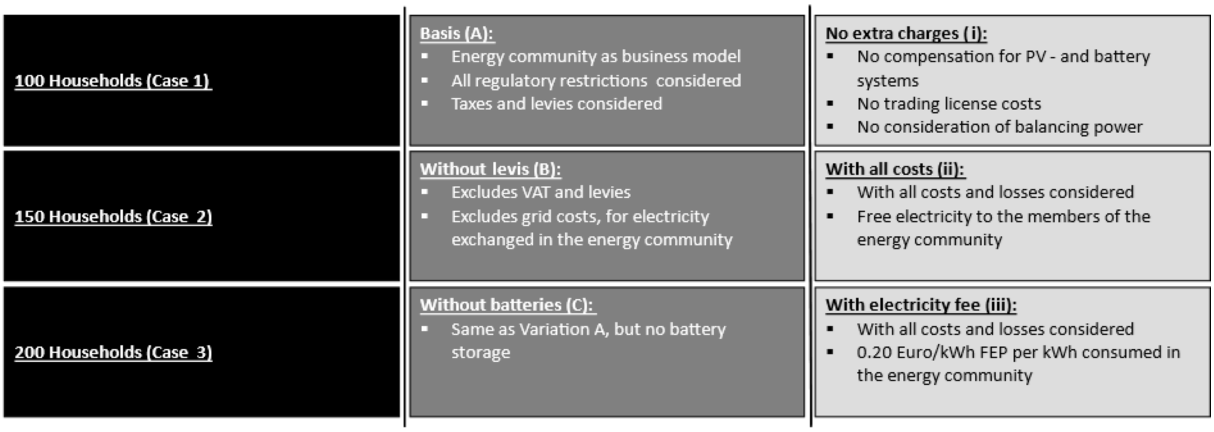

Figure 58: Visualization of the variations and specifications

Considering 100 households (Case 1) in the Energy Community, the critical size to be certified to trade at the balancing market is exactly met considering a battery size of 10 kWh per household.

Basic assumptions:

For the basic assumptions this leads to calculated NCFs as shown in Table 26. Years 1 to 5 reflect the different energy generation via the PV systems due to the different sun radiation. This is calculated with real world data from the city of Aachen in Germany in the years 2013 to 2017. The average reflects the average NCF over those five years. The NPV represents the NPV over a 20 year usage phase by calculating years 1 to 5 four times in a row.

	Year 1	Year 2	Year 3	Year 4	Year 5	**AV**	**NPV**
No extra charges	58.097	58.401	56.302	59.531	60.598	**58.586**	**1.049.012**
With all costs	-65.892	-65.463	-67.724	-64.481	-63.512	**-65.414**	**-1.171.271**
With electricity fee	4.108	4.537	2.276	5.519	6.488	**4.586**	**82.115**

Table 26: Results for case 1 variation A

The results in the simulation show that the Energy Community with a size of 100 households can financially compete already with the proposal of having 100 stand-alone and subsidized prosumers [49]. For scenario ii., the model shows a negative financial outcome of 65,414 Euro per year on average. This consists all costs and losses, and it offers free electricity consumption for the participants of the Energy Community who receive compensation for providing their assets to the Energy Community as described above. If a compensation of 0.20 Euro per kWh is paid by the end customers to the Energy Community for consumed electricity, the average NCF of the Energy Community is 4,586 Euro per year on average for scenario iii.

Without levies and VAT:

In variation B, without levies and VAT, the calculated results are more beneficial for the Energy Community, due to lower costs per exchanged kWh. The idea behind this variation is to use all financial advantages the currently applicable law admits to similar constructs, like the tenant model (see chapter 4.2.3). Hence, in this variation, no VAT and not levies are charged for energy exchanged within the Energy Community. The results are shown in Table 27.

	Year 1	Year 2	Year 3	Year 4	Year 5	**AV**	**NPV**
No extra charges	62.271	62.428	60.048	63.451	65.060	**62.652**	**1.121.816**
With all costs	-61.393	-61.228	-63.641	-60.280	-58.694	**-61.047**	**-1.093.077**
With electricity fee	8.607	8.772	6.359	9.720	11.306	**8.953**	**160.308**

Table 27: Results for case 1 variation B

Readers may expect a significant difference of financial outcomes between variations with and without levies and VAT, since Figure 49 shows a cost reducing potential of more than 50 % per exchanged kWh. With a variation of 4,066 Euro per year (i.) or 4,367 Euro per year (ii. and iii.) the differences are not as high as expected though. This may be due to the fact that the electricity exchange between end customers of the Energy Community is not separately calculated in the simulation model.

Without batteries:

Variation C shows a much clearer financial difference, as depicted in Table 28. Even if the compensation costs for battery storage are dropped, note that the missing battery storage limits the opportunity to participate in the balancing market and therefore the Energy Community in not feasible in economic terms.

	Year 1	Year 2	Year 3	Year 4	Year 5	**AV**	**NPV**
No extra charges	-52.242	-52.926	-51.950	-51.365	-50.205	**-51.738**	**-926.395**
With all costs	-129.130	-129.810	-128.950	-128.500	-127.430	**-128.764**	**-2.305.585**
With electricity fee	-59.130	-59.810	-58.950	-58.500	-57.430	**-58.764**	**-1.052.199**

Table 28: Results for case 1 variation C

Table 29 provides a summary showing the average results for all 27 scenarios.

		100 Households	150 Households	200 Households
Basic	No extra charges	58.586	208.179	395.592
	With all costs	-65.414	54.963	170.112
	With electricity fee	4.586	159.963	310.112
Without levies and VAT	No extra charges	62.652	233.328	398.365
	With all costs	-61.047	58.791	173.218
	With electricity fee	8.953	163.791	313.218
Without batteries	No extra charges	-51.738	-77.606	-103.474
	With all costs	-128.764	-182.352	-235.932
	With electricity fee	-58.764	-77.352	-95.932

Table 29: Overview of the average results

The results validate that the financial benefit rises with a higher number of households, which also leads to a larger amount of generated energy and available capacity. The data also reveal that the step from 100 to 150 households is higher in total, than the step from 150 to 200 households. This can be explained with the Energy Community participating in the balancing market. The added value of capacity over the One MW limitation has a higher impact than the added value of the additional capacity above 1,5 MW. Nevertheless, adding households to the Energy Community also adds financial value to the Energy Community.

In general, the results in all cases are having the same tendencies and allow to derive some general conclusions. If battery storage is not available, the results show that the business model of an Energy Community is not financially feasible in any constellation. This seems reasonable as it is in general not possible to participate in negative balancing markets on the one hand. On the other hand, however, it is not possible to store energy to provide it to the balancing market at a later time. Since electricity is generated with PV systems, it can be assumed that the energy available for the balancing market is already saturated during peak periods. The results summarized in Figure 59 allow the three major conclusions.

(1) The bigger the Energy Community, the better is the financial outcome of the Energy Community in total.

(2) VAT and grid costs for internally exchanged electricity in the Energy Community are not the main cost drivers, hence these costs are no substantial barriers to promote Energy Communities.

(3) Battery storage is mandatory to operate Energy Communities that are economically feasible.

Furthermore, it can also be seen, that the operation with only one MW capacity is hardly beneficial and the economic efficiency depends on the amount to pay per consumed kWh. Nevertheless, the simulation model confirms the potential economic feasibility of Energy Communities, which act as market participants in the balancing market in Germany. The model also demonstrates that the consolidation of prosumer households in Energy Communities is economically more efficient than operating the prosumer households independently from each other, according to other studies. These community benefits are reflected one the one hand in the chance to smoothen the overall energy demand curve and exchanging energy within the Energy Community. On the other hand, are these benefits reflected in the size of the general system, which allows to trade on the electricity market.

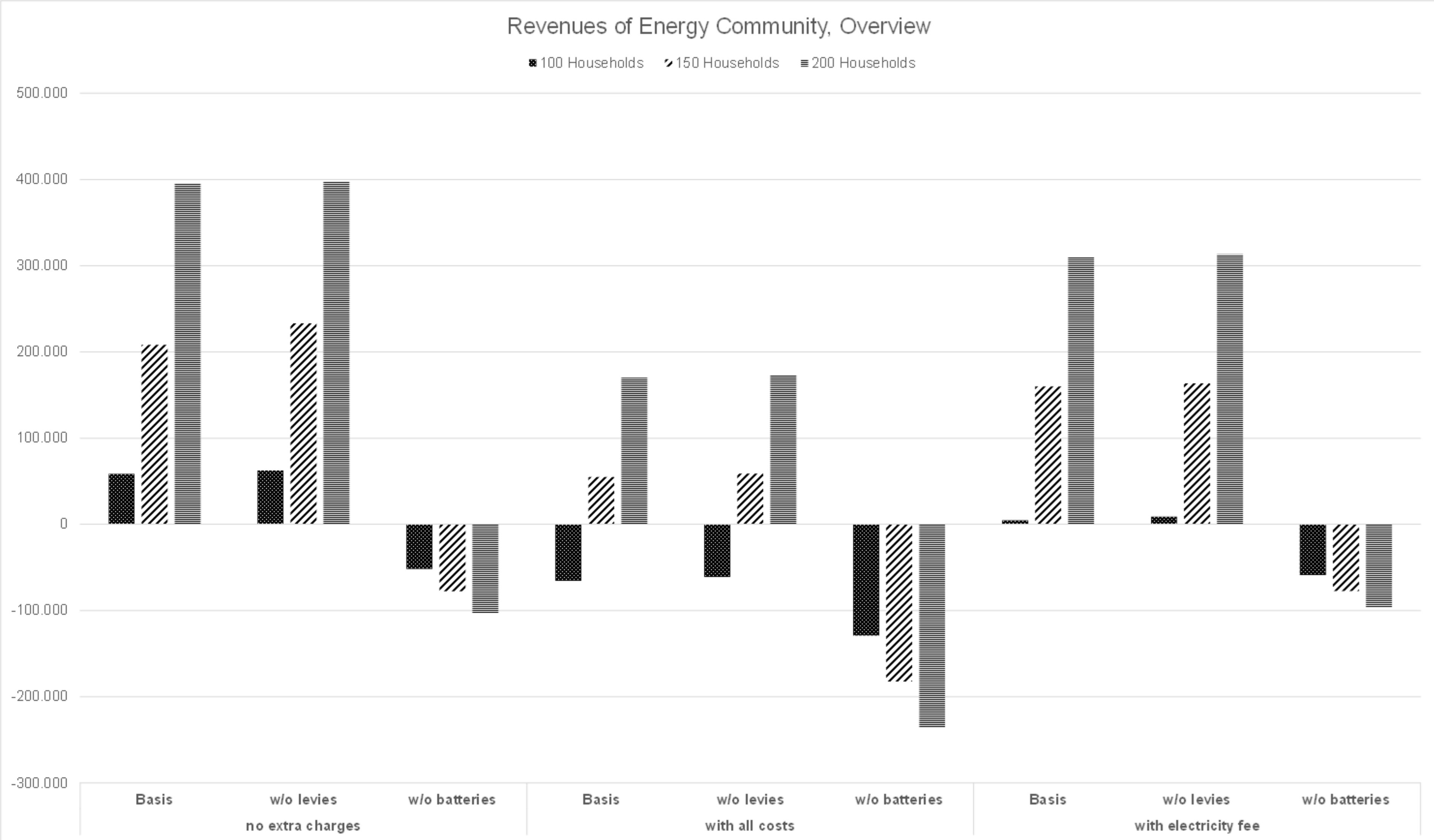

Figure 59: Revenues of Energy Community, Overview

4.5 Conclusion

This paper analyses if it is financially feasible to establish Energy Communities which operates at the balancing market under German market conditions. For this purpose, we modelled a variety of scenarios for exemplary Energy Communities consisting of a number of prosumer households.

The results indicate that decentralised generation and renewably electricity generation is not necessarily associated with higher costs and that establishing such Energy Communities can be financially advantageousness. The underlying business models can not only lower the energy costs for the private households involved but can also contribute to achieving the government's climate goals, even when subsidies are lower or abandoned. Furthermore, Energy Communities do not have to rely on building a complex infrastructure and can therefore accelerate the transition of the energy system towards energy from renewable resources. In addition, transmission and distribution losses will be minimized and the end-customer will be placed in the centre of energy transition. The study shows that storage capacity is mandatory to create financial benefits. Storage systems provide the opportunity to stabilize the local Energy Communities and to increase their self-sufficiency, but storing energy allows communities to participate in positive and negative balancing markets, too, which is the main opportunity for creating financial benefits.

Overall, the simulation model proves the benefits of the Energy Community as a business model. Not only does it pay off to be part of an Energy Community, but it also supports Energy Communities in developing and extending renewable energy generation with limited effort and small costs. Even if, Energy Communities in this simulation are connected to a superordinate grid, this will not be any barrier for running Energy Communities. The combination of decentralized Energy Communities, off- and onshore wind farms and hydro as well as the linked European high-voltage grid can buffer the deficiencies of the local Energy Communities.

Even though government authorities and regulators already subsidize renewable generation in Germany, this paper presents a way to successfully operate renewable generation and storage. In summary, Energy Communities offer many significant advantages, and provide an important alternative for balancing electricity supply and demand already today. This is true not only from a technical perspective, but also from a financial perspective. Last but not least, a higher degree of autarchy against the background of the recent volatility of energy systems is another argument for establishing Energy Communities.

Limitations of this study are, firstly, the necessity to form average values. Even though real data from different years were used, average values still had to be used over the period under consideration. Secondly, this study is limited by the assumption that the households are of similar size and use similar equipment with regard to the PV system and battery. In practice, this is probably rare. With increasing electrification of mobility and heat generation, further research may be needed to consider different consumer segments e.g. consumers who charge their electric car overnight or with specific consumption patterns.

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