Utility-scale photovoltaic & battery storage systems

Techno-economic feasibility study of the new stadium in Freiburg, Germany

Master Thesis

Sophie Török

Aalborg University
Sustainable Energy Planning and Management

Fraunhofer ISE
Institute for Solar Energy Systems

AALBORG UNIVERSITY

Title:
Utility-scale photovoltaic & battery storage systems
Techno-economic feasibility study of the new stadium in Freiburg, Germany

Type of Paper:
Master Thesis

Project Period:
Summer Semester 2019

Supervisor:
Poul Alberg Østergaard

Supervisor extern:
Andreas Hensel

Examiners:
Poul Alberg Østergaard
Lars Boye Mortensen

Page Numbers: 80

Date of Completion:
June 14, 2019

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person where due reference is not made in the text.

Freiburg on June 14, 2019 Sophie Török

Abstract

The highest amount of CO_2 emissions in the European Union is caused by the energy sector. The growing problems due to climate change and thus the need for a decarbonisation of the energy sector has pushed the implementation of renewable energy technologies on a global scale. With the increasing amount of renewable energy technologies new challenges arise, especially concerning the fluctuating availability of produced electricity. One solution to this challenge is to add a battery storage to the renewable energy plant, however, these storage units are associated with high investment costs especially in the utility scale, and are therefore often not taken into consideration. In order to bring forward the implementation of renewable energy technologies among large consumers, the techno-economic feasibility of a utility-scale solar power plant in combination with a utility-scale battery storage is assessed.

This is done through a case study of the new football stadium in Freiburg, Germany. The current practice is to cover the stadium's load with a diesel generator during match, while the remaining base load is powered by electricity from the grid. By investing into a rooftop photovoltaic plant with a battery storage as an alternative, the stadium does not only replace the diesel unit but also provides itself with a system which can create revenues. Given the high capacity requirement of the battery to power a game event and match only occurring 18 times a year, the battery can be used for electricity storage and trade in the remaining time.

In order to assess the feasibility of this system, the load profile of the stadium is identified. Then, three different systems are modelled with the software energyPRO. The first system represents the current practice with the diesel generator (*DG system*). The second system adds a photovoltaic plant to the first system with the diesel generator (*PVDG system*). The third system consists of the photovoltaic plant and the utility-scale battery storage with no diesel unit (*PVBES system*). The assessment is carried out by first identifying the technical performance of the different systems. Then, the relevant investment and operational costs for the different systems are determined. Further expenses like electricity purchase from the grid but also the relevant surcharges, taxes and fees are identified. Taking all the cash flows into account, the economic feasibility is assessed by calculating the net present value of the systems, with consideration of receiving a feed-in tariff or trading electricity on the spot market with the PVDG and the PVBES system. Furthermore, different economic scenarios are considered for the PVBES system in order to improve the economic feasibility.

The results show that under the same conditions, the PVDG system offers the economically most favourable solution, despite the net present value of all systems being negative. Nevertheless, the PVBES system offers more flexibility and allows the stadium operator to consider other revenue options on the balancing market or through power purchase agreements. With these options considered, the PVBES system not only offers the economically best option, but also pays off the expenses with a payback-time between 8 and 16 years. In addition, no CO_2 emissions occur through the operation of the PVBES system.

Table of Contents

Acknowledgement

First I would like to thank my thesis advisor and professor Poul Alberg Østergaard from the Department of Planning at Aalborg University. His suggestions, comments and critics were pivotal in the outcome of this thesis. He always allowed this paper to be my own work, while guiding me into the right direction whenever needed. In addition I would like to thank Dipl.-Ing. Andreas Hensel, my supervisor at Fraunhofer ISE for his input.

I would also like to thank the experts, retailers and project planners who were involved in the development and validation of thisthesis. Special thanks go to my aunt, Dr. Júlia Katalin Török, for taking the time to go through my work and providing her vast knowledge in academic writing to improve the quality of this thesis. Furthermore, I would especially like to thank Dipl.-Ing. Leonhard Probst from Fraunhofer ISE, who made it possible for me to write my thesis at the Institute and provided feedback to my work.

Many thanks go to my family, especially my mother, Eva Sipos, for supporting me during my time at university, and my friend Sini Alhola for the long hours of Skype studying; without her I would not have been able to complete my studies. I would also like to give thanks to Kerstin Schreihans without whom I would not be where I am right now, and to Theresa Kirchweger for pointing out my strengths and inspiring me to work hard. More thanks go to my colleague Konrad Schäfermeier who continually provided me with homemade honey to keep up my strength for writing the thesis.

Finally, I would like to express my gratitude to my Frenchy, Charles Berro, for his continuous support, encouragement and for always believing in me.

The author

Abbreviations

AC	Alternate current
BMWi	German Ministry of Economy and Energy
BESS	Battery energy storage systems
CAPEX	Capital expenditures
CF	Cash Flow
CFSR2	Climate Forecast System Reanalysis 2
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DC	Direct current
DEA	Danish Energy Agency
DG	Diesel generator
dkk	Danish Krone
EEG	German Renewable Energy Sources Act
EC	European Commission
EU	European Union
EV	Electric vehicle
€	Euro
€ct	Euro cents
FIT	Feed-In tariff
FLH	Full-load hours
GHG	Greenhouse-gas
GHI	Global Horizontal Irradiation
GJ	Giga-Joule
GW	Giga-Watt
GWh	Giga-Watt hours
ISE	Fraunhofer Institute for Solar Energy Systems
kVA	kilo-Voltampere
kW	Kilo-Watt
kWh	Kilo-Watt hours
kWp	Kilo-Watt peak
LCA	Life-cycle assessment
LCOE	Levelised cost of electricity
Li-Ion	Lithium-Ion
MW	Mega-Watt
MWh	Mega-Watt hours
NPC	Net present cost
NPV	Net present value
PbA	Lead-acid battery
PPA	Power purchase agreements
PV	Photovoltaic
PVBES	PV and battery energy storage
RE	Renewable energy
t	tonne
TSO	Transmission system operator
TW	Tera-Watt
VAT	Value added tax
TWh	Tera-Watt hours
VRF	Vanadium Redow Flow

1 | Introduction

The energy supply sector is the largest contributor of carbon-dioxide (CO_2) emissions in the European Union (EU), accounting for 29.3% of the total CO_2 emissions in 2014 in the EU-28, followed by the transport and industry sector with 19.5% and 19%, respectively [1]. The main goal of the Paris Agreement, which is to keep the global rise of temperature below 2°C, can only be achieved by a systematic decarbonisation of the energy sector by 2050 [2].

With the Directive 2009/28/EC of the EU, a framework was set to promote renewable energy (RE) technology within the EU. This directive sets mandatory national targets for the share of RE in both energy consumption and transportation. For the support of RE, Germany has set up the German Renewable Energy Sources act (EEG) in 2000. Furthermore, in response to the Paris Agreement the country has set ambitious national targets of reducing greenhouse gas (GHG) emissions for the electricity sector by 40% compared to 1990 levels by 2020, and 80-95% by 2050 [3]. The ongoing energy transition from conventional energy sources to RE, especially photovoltaics (PV) and wind energy is a crucial step in order to achieve these targets. The RE sector is thus one of the fastest growing in Europe and with an ongoing decrease of costs for PV, this trend is expected to continue in the future [4].

1.1 Installed capacity and electricity production

The main sources of CO_2 emissions in the electricity production in Germany derive from brown and hard coal, which made up 37.5% of the electricity generation in Germany in 2018. According to the data from the German Environmental Agency, CO_2 emissions in the energy sector have been reduced by 22.4% in 2017 compared to 1990 levels [5]. In order to achieve the national targets, the amount of RE has to be increased and GHG and CO_2 emissions from fossil fuels have to be further reduced, for example by replacing fossil fuel-based energy generators with PV plants. As of 2019, sources like brown and hard coal still hold a significant amount of the total nominal capacity, with 21.2 GW and 23.7 GW, respectively [6]. According to a study from [7], yearly additional capacities of 8 GW of PV and 4 GW of onshore wind are required to cover 65% of the net electricity consumption of Germany by RE by 2030. Furthermore, if the country is to be supplied almost entirely by RE by 2050, additional 5-7 GW capacity of PV per year are required in order to reach this goal [8]. However, in 2018, only an additional nominal capacity of 3.59 GW PV was installed in the country (1.66 GW were installed in 2017) [9] which does not catch up to the target capacities if the national goals are to be achieved.

Figure 1.1 shows the installed or nominal capacity available in Germany in June 2019, listed by energy source. It should be kept in mind that this figure does not take into account the net electricity production which depends on the operation hours of each source.

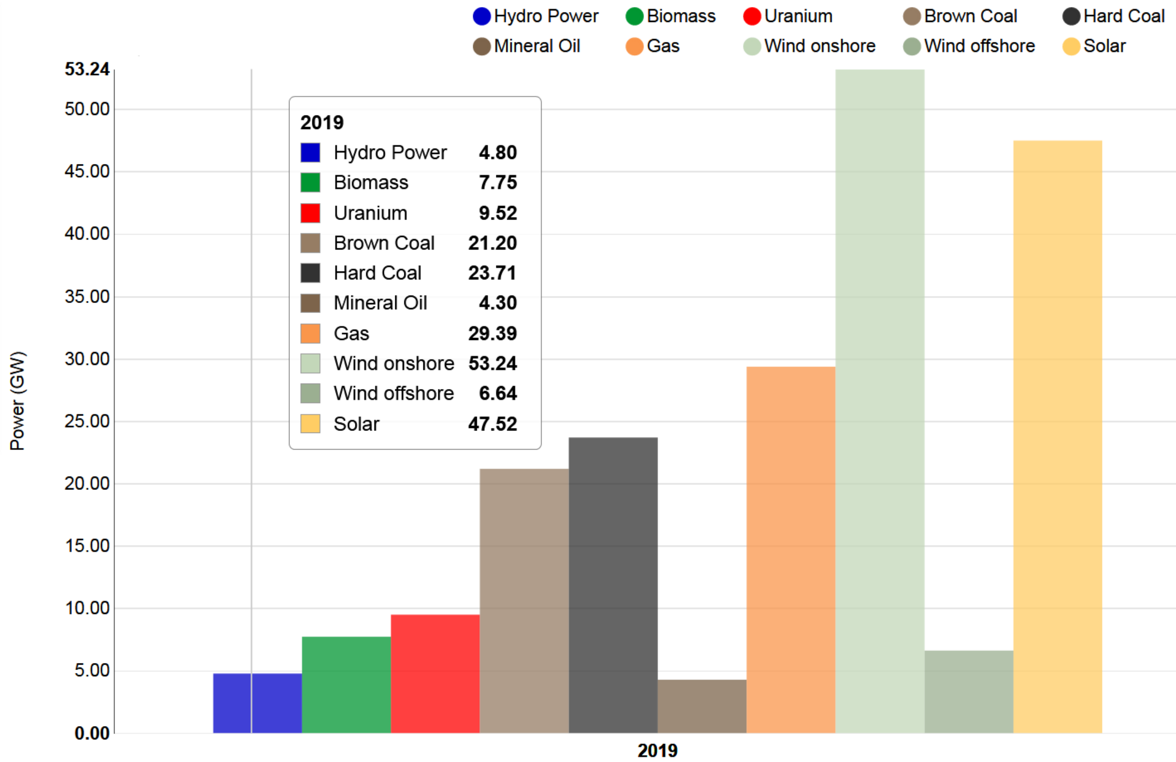

Figure 1.1: Installed capacity in Germany in June 2019 by energy source (*Illustration from www.energy-charts.de [6]*)

It can be seen that onshore wind has the highest installed capacity (53.2 GW) followed by solar (47.5 GW) and gas (29.4 GW). The net electricity production of Germany by energy source is shown in Figure 1.2 below.

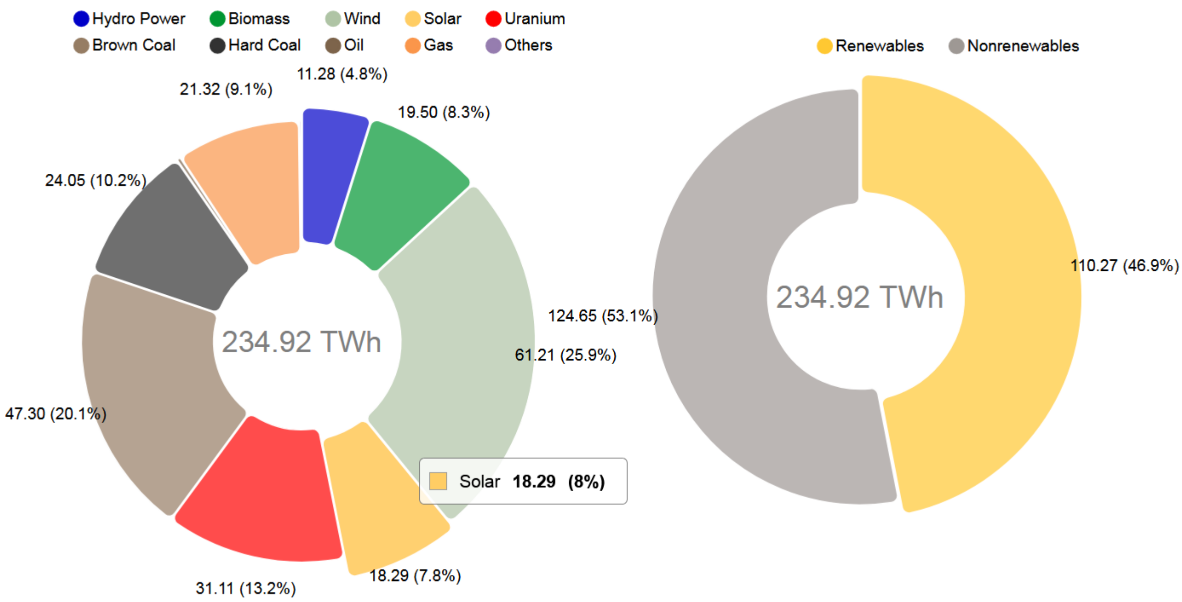

Figure 1.2: Energy Production in Germany in 2018 by energy source (*Illustration from www.energy-charts.de [6]*)

As of May 2019, around 47% of the German net electricity production is covered by RE sources (Figure 1.2 right side), with wind power being the most dominant RE source (25.9%), followed by PV (7.8%) and biomass (8.3%) (Figure 1.2 left side). The remaining 53.1% are covered mainly by fossil fuels, with brown coal being the dominant source (20.1%) [6].

1.2 Challenges of PV electricity production

The integration of PV power plants into the energy system poses various challenges on a technical, economic and regulatory level.

Firstly, the power output of various RE sources is characterised by a highly fluctuating nature. With the increasing amount of wind and PV, there still remains a residual load which cannot be covered at given times or areas. The residual load is then covered by controllable units which can be either from other renewable (e.g. hydropower) or non-renewable (e.g. coal) sources. Storage systems can support covering the remaining demand and therefore decrease the need for supply from non-renewable energy sources [10].

Secondly, as the national funding for open-site PV systems has phased out and transformed into a tender system, the installation of new open-site solar parks in Germany has decreased as well. Furthermore, with the need of larger capacities for both PV plants and storage systems, larger areas are required which might trigger resistance with locals or environmentalists who would prefer keeping the natural environment of the area. Indeed, for the increase of PV capacity in the following years it is recommended by [8] to put out 38% of the tenders for rooftop areas in order to respect the ecological factor of the use of open-site PV plants. What is more, as solar energy is a distributed energy source, grid architectures require a shift from traditional, centralised energy systems to more distributed, decentralised ones [11]. It is therefore important to look into implementation possibilities in cities, especially on rooftops. Estimations were made about the rooftop potential in Germany and a potential area of between 965 km^2 and 1 516 km^2 was determined which could provide area for between 193 GWp and 304 GWp power with a module efficiency of 20% [3]. Increased local electricity production in cities would also benefit in terms of transmission, since more energy could be consumed locally instead of being transported to other locations.

Current popular measures are grid expansion or curtailment, however, grid expansion requires high effort, and curtailment leads to additional costs for the end-users. That is because remuneration to the electricity producers for curtailment is financed by the EEG surcharge that is part of the end-user electricity costs and will be elaborated on in the following sections. In 2017, curtailment measures resulted in expenses of up to 420 billion €, which mainly derived from the remuneration that is paid to the operators of the curtailed power plants from the EEG budget [12]. What is more, the grid expansion is expected to bear costs of around 52 billion € as a publication of the four Transmission System Operators (TSO) in Germany states [13].

The use of battery energy storage systems (BESS) can balance the fluctuating nature of electricity generation by PV plants and support rooftop PV installations; however it poses a range of new problems like high costs, area requirements in the large scale and environmental or resource issues due to certain materials that are used. Another option would be alternative storage methods like power-to-gas, power-to-heat and power-to-x [14], which are not looked into further in this thesis as the technologies are often not mature enough for implementation.

1.2.1 Economic Aspect

In order to foster the energy transition, RE technologies need to be able to keep up both technically and economically with fossil fuel based alternatives. The prices for PV plants have been constantly decreasing in the past decade. While in 2006, the costs for rooftop PV plants in Germany were above 4 500€/kWp, the prices in 2017 have since decreased by 75% with costs of between 600 and 1 500€/kWp [15]. In one study, the levelised cost of electricity (LCOE) in Germany for the year 2018 for different energy sources is determined with results shown in Figure 1.3 [16]. It can be seen that especially utility-scale PV plants (3rd column from the left) have a comparably low LCOE which is due to the decreasing costs with and increasing power capacity of the plant. This economy-of-scale can be explained by the fact that system components can be produced and thus purchased and installed for cheaper prices in high numbers [9]. The wide range of LCOE within fossil fuel powered plants is due to the dependence on factors like fuel price and CO_2 certificate prices [16].

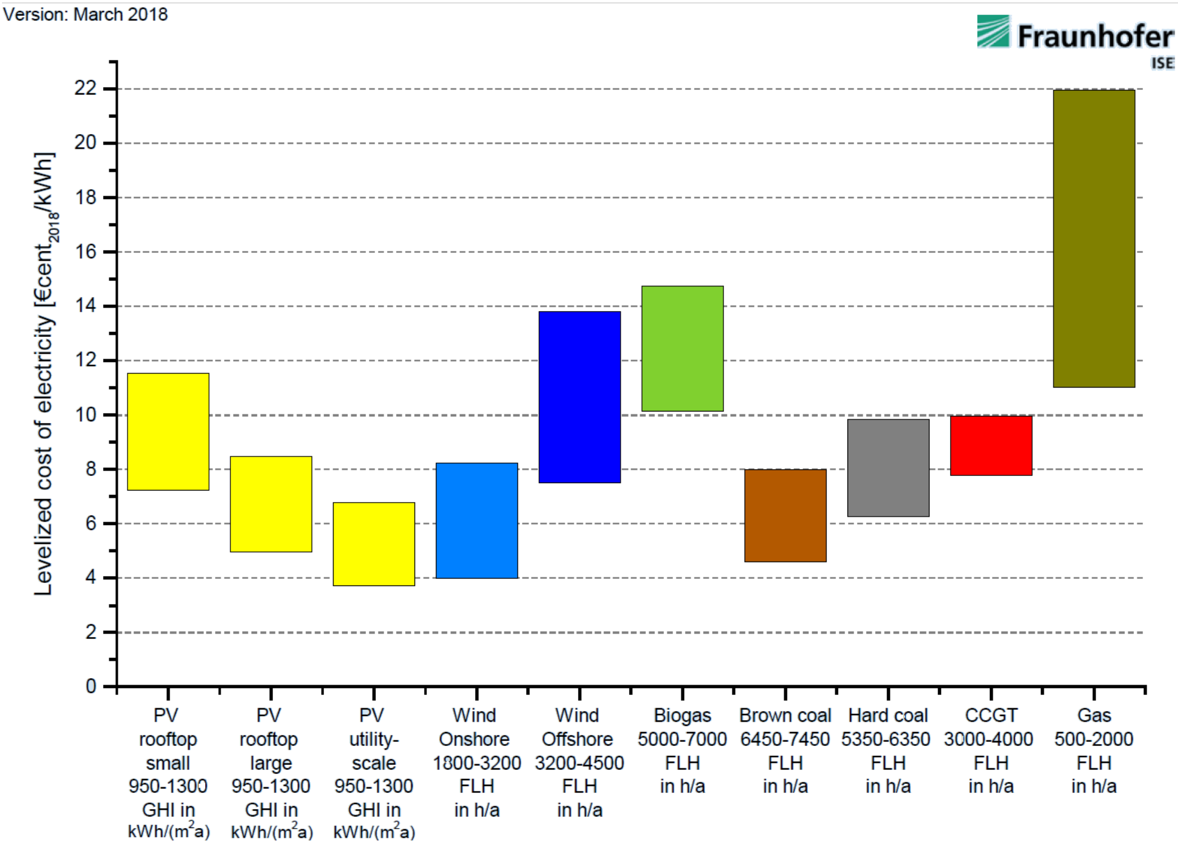

Figure 1.3: LCOE costs of different energy sources, showing the global horizontal irradiation (GHI) and full load hours (FLH) data for PV and other sources, respectively (*Illustration from Fraunhofer ISE [16]*)

The growing and rapidly changing PV market, especially in the pricing, increases the requirement of more up-to-date price analyses and awareness raising [17]. According to opinions from different sources, PV is often discarded as an economically feasible option because of calculations being carried out with old prices, while the overall costs are constantly decreasing [18]. With the decreasing prices of PV modules, which currently make up about 40% of the total investment costs, the overall investment costs for PV plants in Germany have drastically changed. Indeed, many models of future energy systems tend to underestimate the role of PV, expecting a far smaller contribution despite the favourable price developments, policy changes or other factors that support the implementation of more PV [19]. Therefore, many researchers and experts in the PV field are trying to raise awareness in Germany about the necessity of the integration of more RE than it is intended in current policies [20].

As for battery storage, even though prices especially for Li-Ion batteries have continuously decreased in the past, it is hardly profitable to install a battery storage unit without financial support [21] for grid-connected used. Still, despite the low profitability the trend of adding battery storage has increased in Germany in the past years due to financing schemes [22]. According to [21], given the advantages of increased self-reliance and therefore independence, but also due to the increasing prices for electricity, this trend will continue. The increased independence from the public grid raises the question on how the energy market, especially electricity prices, will be influenced and transformed if more and more residential and commercial customers aim towards self-reliance. Nevertheless, the EEG surcharge is paid for every kWh consumed electricity (although there is a 40% reduction for RE) irrespective of whether the electricity is purchased from the grid or consumed from privately owned power units, unless the units are below 10 kWp. Therefore the national budget for the energy transition will only slightly decrease with increasing self-reliance [21].

With the decreasing prices for PV and simultaneously growing electricity prices, the aim for increasing self-sufficiency in Germany are resulting in more and more investments into PV and battery storage systems (PVBES), despite the economic disadvantages. For now, PbA batteries are dominating the global market [23], although with the growing demand, Li-Ion is expected to overtake lead batteries on the global market within the next decade [24]. This is mainly due to the various technical advantages of Li-Ion, which are further elaborated on in Chapter 5, that make Li-Ion more preferable than lead. Retail prices of Li-Ion batteries have halved between 2013 and 2017, according to research from the Technical University of Aachen, Germany. This trend is forecasted to continue and can already be seen on the German market since new batteries purchased in 2017 in Germany were almost exclusively Li-Ion batteries [25]. The technical and economic feasibility of PVBES with household but also utility-size capacities thus becomes more and more an important field of research.

1.3 German Renewable Energy Sources Act

The liberalisation of the energy market in Germany towards the end of the 90s brought various advantages, as more actors are able to enter the market and consumers can choose their provider. It also provides more transparency flexibility in terms of planning, forecasting and trading. This is especially beneficial for the integration of RE sources with their fluctuating characteristics [26] and since the liberalisation, the amount of RE has been constantly increasing. The consequentially occurring Merit-Order effect has resulted in record low of wholesale electricity prices. Yet, the end-use electricity prices for both residential and non-residential customers in Germany have been constantly growing in the past years. Indeed, Germany has one of the highest residential and non-residential electricity prices within the EU-28 [27]. This is due to the growing surcharge of the EEG which is used to finance the energy transition. The net electricity price in Germany for household consumers consists of taxes (22%), levies (31%) and the network charge (23%) [28], see Figure 1.4.

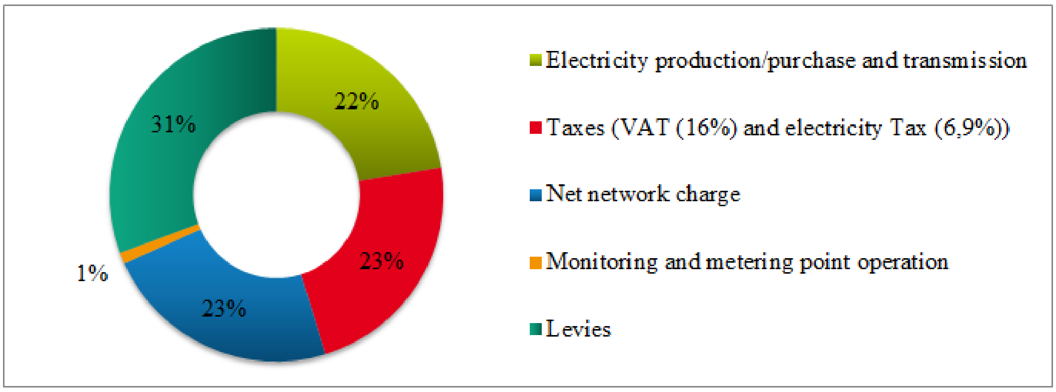

Figure 1.4: German electricity price composition (*Own illustration, data from [29]*)

The main aim of the EEG surcharge was to support the installation and operation of RE power plants for example by financing a feed-in tariff (FIT) that is given to RE plant operators for a time period of 20 years. This encouragement to invest in RE as well as the drastically dropping investment costs for renewables resulted in a tremendous growth or the RE industry in the beginning of the millennium. After multiple reviews and updates of the EEG, in 2017 the funding rate for renewables was changed. For PV plants a cap of 750 kW for the capacity was set. Below that capacity, the FIT is still fixed depending on the size of the plant, and PV plants larger than 750 kW have to take part in a tendering process that will define the FIT. Since then, electricity prices for PV plants above 750 kW were set from between 4 €ct/kWh to 9 €ct/kWh [29]. In order to pay the financial support of RE integration and the FITs, the EEG surcharge was introduced to all electricity consumers, which is part of the levies in the price breakdown shown in Figure 1.4. The amount of the surcharge is set on a yearly basis depending on factors like expected spot market prices, the national total final consumption, the installation of additional RE power plants, and the current EEG account balance and cash reserve [30]. The surcharge has been constantly increasing since its introduction in 2000 until it reached a peak in 2017. Indeed, in 2000 the EEG surcharge was 1.73 €ct/kWh, while in 2017 it has grown to 6.88 €ct/kWh and as of 2019 has dropped to 6.4 €ct/kWh [9]. This growth, but also the growing network charges with increasing RE feed-in as well as the tax schemes are responsible for the growing electricity prices.

Consequently, self-sufficiency for private households but also for the industry becomes more and more economically favourable through RE sources and BESS [31, 32]. Self-sufficiency of households of around 20-40% can already achieved with rooftop PV plants alone, meaning that only the remaining 60-80% of electricity is purchased from the grid. By adding a battery storage unit, the self-reliance can increase to levels between 45-80% depending on factors like load profile, consumption or capacity. Taking this into account, the electricity costs can be reduced as less electricity has to be purchased from the grid. Given that electricity prices have surpassed the FIT levels since 2012, more and more consumers will likely invest in a BESS to avoid high electricity costs in the future [31]. The most commonly used battery types to combine with PV plants are lithium-ion (Li-Ion) batteries and lead-acid (PbA) batteries [32].

Another way to avoid high electricity tariffs is to trade it directly on the market. The energy market in Germany consists of the energy stock market, which can be divided into a futures market (European Energy Exchange (EEX)) and a spot market (EPEX). The EPEX is further divided into Day-Ahead and Intraday, where the former is divided into single hours or multiple hour blocks and the latter into 15 minute blocks which can be purchased. Furthermore, there is the over-the-counter option, where products and prices are negotiated individually. Finally, there is an option to generate revenues from the balancing market, where specific amounts of electricity are reserved and controlled by the TSO in order to maintain grid stability in exchange for remuneration [33].

The large-scale implementation of RE in cities, especially for utility-size plants could be a way to support the German energy transition, lower the electricity expenditures of businesses with significant electricity demand and even create revenues for the investors by feeding excess electricity into the grid or selling it on the electricity market. However, due to the divergence of electricity production by RE like wind and PV, new challenges arise which can potentially be solved by PVBES. This thesis therefore looks into the electricity supply of utility-scale businesses that use fossil-fuel based units, and analyses the possibility of RE integration and even the replacement of fossil-fuel based units with a battery storage.

1.4 Case study

The research is carried out based on a real case, namely the new stadium of Freiburg (referred to in this thesis as the "new" stadium or *Wolfswinkel-Stadion*), which is being built at the moment and supposed to replace the current one. An illustration of the new facility is shown in Figure 1.5.

Figure 1.5: Design of the new stadium in Freiburg (*Illustration from [34]*)

The stadium has an available rooftop area for a PV plant, is located in the north of the city of Freiburg, and has and electricity load profile which is constant during the year except for match days, where the peak load can go above 1 MW. As many other stadiums in Germany, the old stadium in Freiburg (referred to as *Schwarzwald-Stadion* or "old" stadium in this thesis) is powered by a diesel generator (DG) throughout football games when the electricity demand reaches its peak. This is done in order to ensure a secure supply of electricity and being able to keep the television broadcasting of the game running in case of a power outage. However, with the construction of the new stadium, the goal is set to improve the environmental image of the city of Freiburg even further by decarbonising the energy supply. Therefore, the heat demand is to be supplied by district heating from a utility company located nearby.

In order to further offset the carbon footprint, a 1.8 MW PV plant is proposed to be built on the rooftop. The electricity from this plant can be used to supply the stadium's electricity demand and excess electricity can be fed into the grid. However, with the PV plant alone the DG is still needed for secure supply. To avoid the use of fossil-fuel based units, a PVBES is proposed instead, which could not only support the stadium demand during match but also store the electricity from the PV plant, increase the self-reliance of the stadium which would financially be a benefit, and even create additional revenues for example by buying electricity at times of low prices and sell it at times of high prices on the electricity market. This is especially important in order to recover the investment costs for the battery, which are significantly higher than the DGs, as it is shown in Chapter 5. Taking the stadium as a case study, an economic assessment is carried out with different scenarios considered. By looking not only at energy market trading options but also power purchase agreements (PPA) which are becoming more feasible with PVBES, the amortisation of the expenses for the whole system is aimed at within a time-frame of 20 years.

1.4.1 Existing research

The role of PV in the energy transition is widely researched [4, 11, 19, 35–40], with some research claiming that the potential of PV is often neglected in energy system modelling and predictions [19]. The IPCC has researched the role of the energy transition for reducing carbon emissions in [38] and [39], however, the focus on solar PV is quite low. PV in Germany is widely researched in course of the energy transition, including reports on general facts [9, 41], the role of PV in the German (future) energy system [8, 42, 43] and historic and future price developments of PV [17, 18, 44, 45]. The integration of PV in urban energy systems for large scale rooftop PV is researched in [46], studies focusing on Germany are [3] for the whole country and [47] for the city of Berlin. Furthermore, the profitability of residential PVBES in Germany is evaluated by using a simulation model in [48]. Business case approaches for PV in general are addressed in [48–52] and for the German area in [31, 53], where the profitability potential of PV lies not only in grid feed-in but also self-consumption. Specific challenges faced through RE and PV integration are discussed or researched in [37, 54]. In general, most research suggests holistic solutions for overcoming the challenges of large-scale RE implementation on a technical, societal and regulatory level. Furthermore, these studies agree that PV is becoming one of the main suppliers of electricity, with many challenges still to overcome for large-scale implementation. Large-scale rooftop power plants in Europe can be found for example in Sweden (1.5 MW capacity) [55], Norway (1 MW) [56] and also in Härtensdorf, Germany, where a 1 MW PV plant was installed on the roof of 16 buildings [57].

Various road-maps and other studies about battery storage technologies can be found in [14, 24, 58–62]. PVBES are addressed in [31, 53, 63] with focus on residential levels [51, 64, 65]. However, this research is mainly focused on the technical feasibility and only briefly addresses the economic feasibility. The economic feasibility of PVBES is assessed in [66] with the conclusion that these systems are only profitable with incentives, however, the context of the research is set for Italy. Alternative business strategies with PVBES in the German market case can be found in [21, 32]. Operation strategies for making PVBES profitable are assessed in [53, 67]. The main outline to be taken from these studies is that Li-Ion batteries are gradually overtaking lead battery technologies on the market global market. Furthermore, from new battery technologies, the Vanadium Redox-Flow (VRF) technology seems to be a promising one that is gaining more and more awareness in Germany. Research about the consequences of BESS operation on the electricity market in the context of South-Korea can be found in [68]. Freiburg is not the first city to build a PV power plant on top of their stadium. The Kaohsiung World Stadium in Taiwan has PV all over the roof with a nominal output power of 1MW [69]. In New Delhi, India, a 1 MW PV plant was built on top of Thyagaraj Stadium in 2010 [70]. Finally, the Allianz Riviera stadium in Nice, France is the first stadium to be a plus-energy stadium building, meaning that more RE is produced by the facility in a year than imported from other sources [71]. Concerning battery storage, one stadium was identified to have a BESS installed, namely the Johan-Cruyff-Arena in Amsterdam, Netherlands, with a net available capacity of 3 MWh [72].

1.5 Scope

With the goal to reduce CO_2 emissions and provide energy more and more from renewable sources, Germany is continuing with the energy transition and thus also facing the challenges that the integration of more RE results in. The national climate target will probably not be reached in 2020 according to various experts [20] and additionally, the increasing amount of decentralised electricity sources from RE in the grid requires a more stable and expanded grid which is connected to high expenditures. Furthermore, the profitability of RE like PV is still questioned when compared to fossil-fuel powered sources, as the price for economic calculations is not up-to-date even though component costs are rapidly changing [73]. Therefore, an overall assessment of current costs for a utility-scale PVBES system powering a stadium is carried out for the determination of the currently relevant economic feasibility. In addition, new selling strategies of electricity should be identified in order to increase the profitability of PVBES of this size.

1.5.1 Research Questions

This study aims to investigate the economic feasibility of supporting the electricity supply and even to replace the DG unit of the stadium. Given the increasing electricity prices and the need for energy generation with less emissions, the partial replacement of a DG with solar energy and a BESS could be an exemplary representation of how RE power plants could improve a business's economy and environmental image. In addition, possible improvements in terms of economic feasibility can be considered by looking at the effects of new technologies on the overall system costs.

In order to address the multiple issues and opportunities that were pointed out in the previous sections and carry out the proposed research, following research question and sub-questions are guiding this thesis:

How can the Freiburg stadium's current electricity supply system be changed from diesel units to a utility-scale PVBES, what are the technical, economic and environmental consequences and what economic factors hamper or support this transition?

- What is the stadium's electricity supply with only DGs, what are the costs for the system and how high are the CO_2 emissions?
- How can a utility-scale PV plant combined with battery storage replace the DGs, supply the stadium in Freiburg and what is the economic feasibility??
- What electricity selling scenarios could improve the techno-economic feasibility of this system in order to pay back the high investment and operation costs?
- What are the environmental benefits in terms of CO_2 emissions during operation?

1.5.2 Thesis Structure

Three different systems are analysed, of which the first referred to as *DG system* in Chapter 3. Chapter 4 looks at a system similar to the DG system, with a utility-scale PV plant added to supply the electricity load. This is referred to as *PVDG system*. Finally, the *PVBES system* considers a utility-scale BESS in order to replace the DGs and ensure a secure supply of electricity during match in Chapter 5. Chapter 6 then looks at alternative ways of making profit with the PVBES system by looking at different possibilities to sell electricity in the most profitable way. A discussion in Chapter 7 critically reflects on the methods, delimitations and the applicability of the results in a broader perspective before the thesis is concluded in Chapter 8. The thesis structure is represented in the graphic in Figure 1.6 with the boxes referring to each chapter of the thesis.

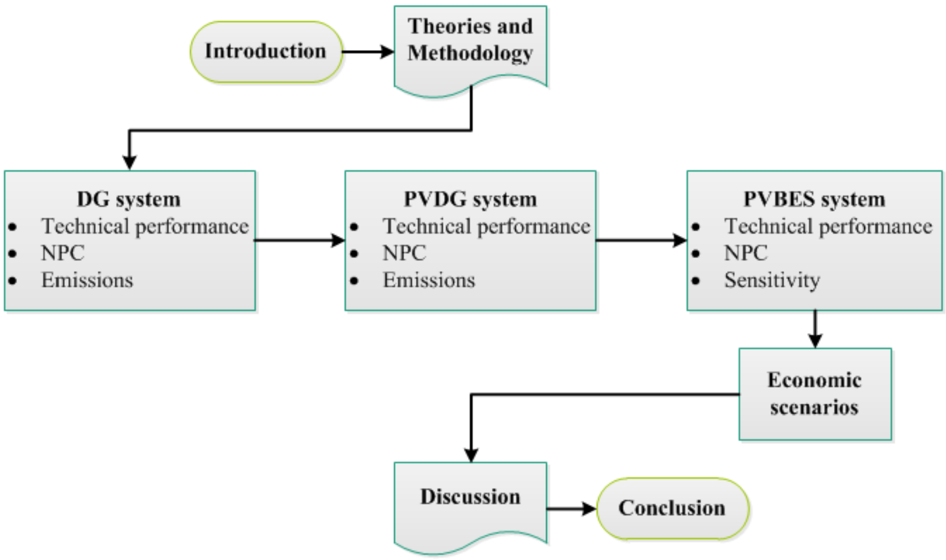

Figure 1.6: Graphical representation of the thesis structure

2 | Theories and Methodology

This chapter gives a list of assumptions that apply for this research that were made in order to narrow down the scope of the calculations. Then follows a section with the theoretical framework concerning the subject of RE transition from fossil fuel alternatives addressing utility scale investors or operators. Finally, the methods of collecting data, calculating the capital expenditures (CAPEX) and operational expenditures (OPEX), as well as the advantages and disadvantages of the methods used is discussed in the later sections.

2.1 Terminology and Assumptions

For this thesis a few assumptions are made, mainly to simplify the process of answering the given research questions.

The following assumptions were made and are applied in this thesis:

- In the course of 20 years no unexpected costs like failure of units, destruction through external forces like vandalism, climate conditions or similar occur and influence the production and OPEX.
- The cost of inverters which have to be replaced after approximately 10 years is neglected.
- The stadium operator is the owner and operator of the DGs, the PV plant, and also the battery storage.
- Residential scale refers to sizes up to 10-15 kW.
- Commercial scale refers to sizes from 15 kW to 750 kW.
- Utility scale refers to sizes above 750 kW.

2.2 Theoretical Framework

The theoretical framework addresses the public awareness that exists in connection with RE, especially PV, and utility-scale battery storage systems. The energy transition is not proceeding fast enough in order to reach the different goals set nationally and internationally [20]. The reason for this and the steps to overcome misleading perceptions, as well as the aim of this study to take some of the steps in favour of PV and battery storage technologies, is described in this section. Focusing more on the case itself, the change of ownership in course of the proposed technological change is reflected on.

2.2.1 Choice Awareness

The analysis of new energy systems requires an overview of the various influential factors that could impede the transition or implementation of the new system. In this case, the switch from the well-known method of using DGs to supply stadiums with electricity during a game to RE and a battery storage can by viewed as radical technological change, which is part of the choice awareness theory [74]. Radical technological change describes a transition where more than one of the five constitutes of technology, namely Technique, Knowledge, Organisation, Product and Profit are changed [74]. In case of the stadium, the replacement of DGs with a PV plant and a battery storage poses a change in the technical components. Furthermore, this shift from the one entity that controls the stadiums electricity supply to new actors, like the operator of the PV plant and the battery but also potential customers who the electricity can be sold to, results in an organisational change. The concept of selling electricity from RE on the market requires knowledge about how the market operates and what strategies are the most profitable for the given system. Finally, new selling strategies can result in higher profit as the electricity is now bought from the PV plant operator, who can make additional profit with new market strategies when the electricity is not needed for a game in the stadium. On the other hand, from the stadium operator's point of view, the use of the stadium can be expanded to more than just to host football games. These possibilities are discussed later in Chapter 6. The only constitute which is not affected by switching from DGs to solar power is the product, which is electricity.

The energy transition is often hampered by "false" collective perception, like the belief that RE cannot be as optimal as fossil fuel units neither from a technical nor financial aspect. There are different reasons for this conception, which mainly originate in different organisations working towards keeping the system as it is since it is the most profitable for them this way, like the oil or gas lobby [75]. The difference in investment and operation costs also plays a crucial role when considering choice awareness, since there might be a lack of common knowledge about current (decreasing) prices for example for PV plants and battery storage. On the other hand, battery storage for balancing the fluctuations of RE production considerably add to the already high investment costs for the RE plant, which only add to the common conception of RE not being as economically 'attractive' as conventional, fossil fuel based units. The result is that stadium operators are kept in a mindset where they believe they have no choice than to maintain in the status quo. A methodology of how to raise choice awareness is given by [76], which can be divided into following four steps (Figure 2.1):

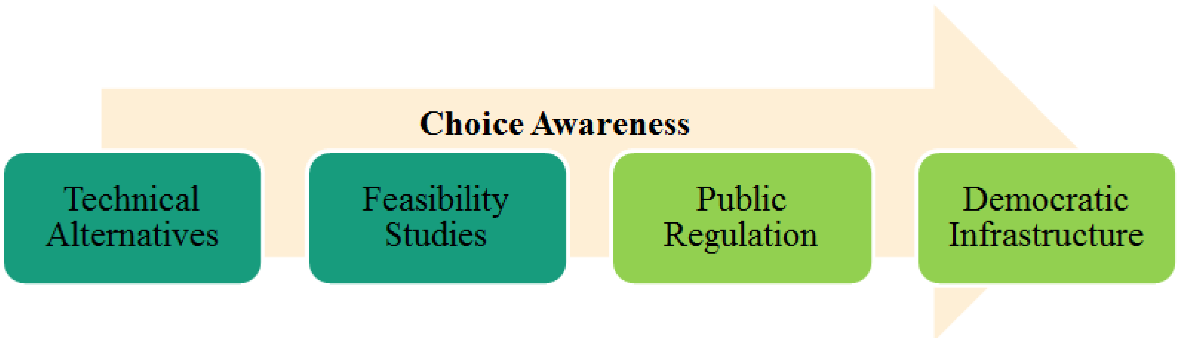

Figure 2.1: Strategies for raising Choice awareness (*Own illustration with data from [76]*)

This thesis deals with the first two steps, where technical alternatives are shown. For the technical alternatives, the current system described in Chapter 3 is compared to two alternatives, the PVDG system in Chapter 4 and the PVBES system in Chapter 5. These also comprise a techno-economic feasibility study, as that is a key factor for implementing a radical technological change. Additional factors like environmental benefits and socio-economic factors are also part of the second step. Furthermore, the application of the case to other contexts is an important requirement, which is why it is discussed in Chapter 7.

The analysis of public regulations is the next step after the technical and economic feasibility, however, these are only briefly discussed in this thesis due to time and resource constraints.

2.2.2 Case Study

The thesis aims to point out the selling possibilities of utility-scale PVBES systems by taking the stadium in Freiburg as an example. By narrowing down the thesis to this case, specific solutions are identified for given factors, like the location, available area for the PV plant or the geographical surrounding. When choosing to conduct research through a case study, the limitations of this approach must be understood and the applicability of the case on other contexts identified. As [77] writes, the goal of a case study is to define parameters that can be applied in other contexts as well. Case studies were often viewed as non-scientific, invalid approach by various sources, as [78] points out in his investigation about the bias on case studies. He addresses the five common misunderstandings in case studies, of which a relevant one would be the generalisability of a single case in a broader perspective. [78] argues by comparing case studies to the context-based learning method of humans learning which leads to the conclusion that case studies provide better understandings about a specific topic. He also agrees to the insight that disciplines, whether it may be in social sciences or other fields are ineffective without given exemplary studies. In order to discuss new selling scenarios for PV plants combined with battery storage, it is therefore important to have a representative case that can serve as future reference for other, similar projects with different contexts. [79] writes in favour of case studies by showing the independent use-values of case studies. To her, a single-case can either serve as a "theory-breaking rock" or a "rolling snowball". So, by using a case to exemplify a given hypothesis (e.g. "battery storage in combination with PV plants are not profitable"), one can either support a common perception (snowball effect) or show that there are indeed cases where the hypothesis can be contradicted for example by assessing the feasibility of the respective case [79]. The generalisability of this study is discussed later in Chapter 7.

2.2.3 Feasibility study

[80] names feasibility studies as the answer to the question of which alternative is most feasible for solving a given problem. He furthermore gives five questions that are to be considered before conducting the feasibility study. The proposed solution is the most feasible

- compared to which alternatives?
- to whom?
- in meeting which objectives?
- within which time horizon?
- including which consequences? [80]

Results of feasibility studies may vary strongly depending on the answers to these questions. As the general supply system of a stadium is powered by DGs, a direct comparison can be made between the current common practice and the proposed alternative with PV and battery storage. The business feasibility of this project is carried out from the aspect of the stadium operator, who is the investor, and thus owner and operator of the different units proposed in this thesis. The stadium operator's objectives are taken into account, which are primarily cost-effectiveness, but also the implementation of innovative alternatives, environmental sustainability and maintaining a somewhat sustainable reputation [71]. The time horizon for the study is set for 20 years, as it is the average lifetime given by retailers for both PV plants and certain battery storage technologies (depending on their operation management). When looking at the consequences for the business-economic feasibility of the project, the economic calculations of all systems offer an idea of future financial consequences which, in the most favourable scenario, are profitable for the investors.

2.2.4 Change of ownership and expenses

An important factor in changing the currently common system into one powered by RE is how the cash flow (CF) is affected by this transition. The changes are shown in Figures 2.3 and 2.5, where red arrows indicate expenditures and green arrows indicate incomes. The boxes around the units and the operator indicate the ownership of the system. "Stadium" represents the stadium operator and CFs are calculated from the operator's perspective.

In the DG system, the stadium operator carries expenses of the diesel unit and pays for the electricity to supply the base load. This system and its expenses are shown and calculated in Chapter 3. As of today, stadium operators own DGs which are used to power the stadium's electricity load during match. This is done in order to relieve the grid but also to ensure security of supply for an uninterrupted transmission of the event. The base load is supplied from the grid. Figure 2.2 the graphical representation of the ownership and electricity purchase.

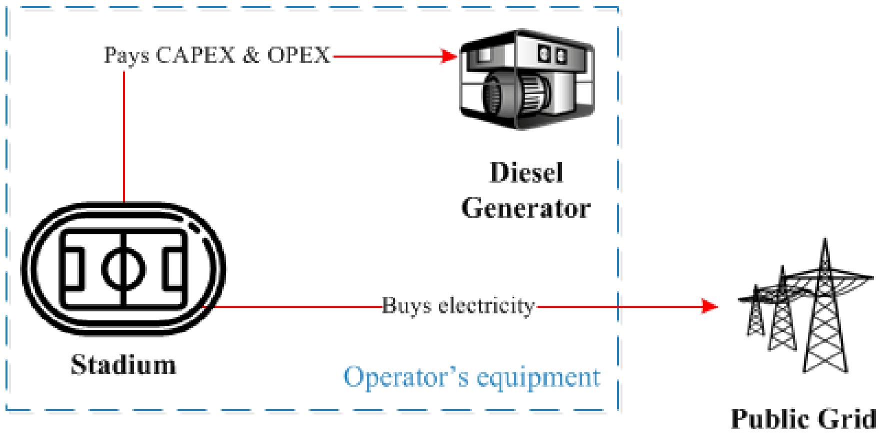

Figure 2.2: Ownership model of the common electricity supply for a stadium with DG and the grid

In the case of this thesis, the stadium also owns a PV plant that is built on top of the stadium. In Figure 2.3 the graphical representation of the ownership and electricity purchase is given.

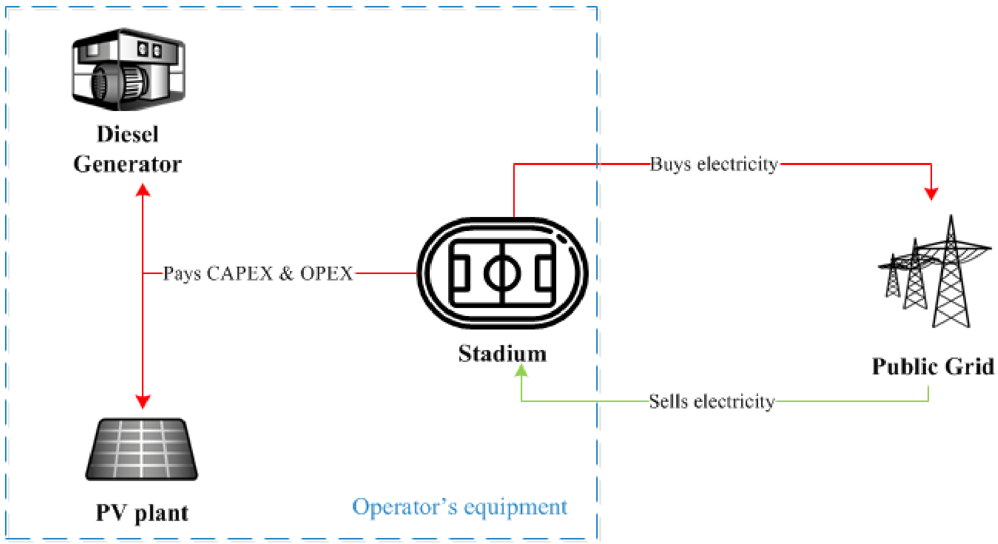

Figure 2.3: Ownership model of the electricity supply with a DG, a PV and from the grid

By replacing the diesel unit with the battery storage system, the utility company would be added as a new entity, see Figure 2.4. The ownership model would change since the stadium operator buys all electricity from the grid and utility company who own the battery storage.

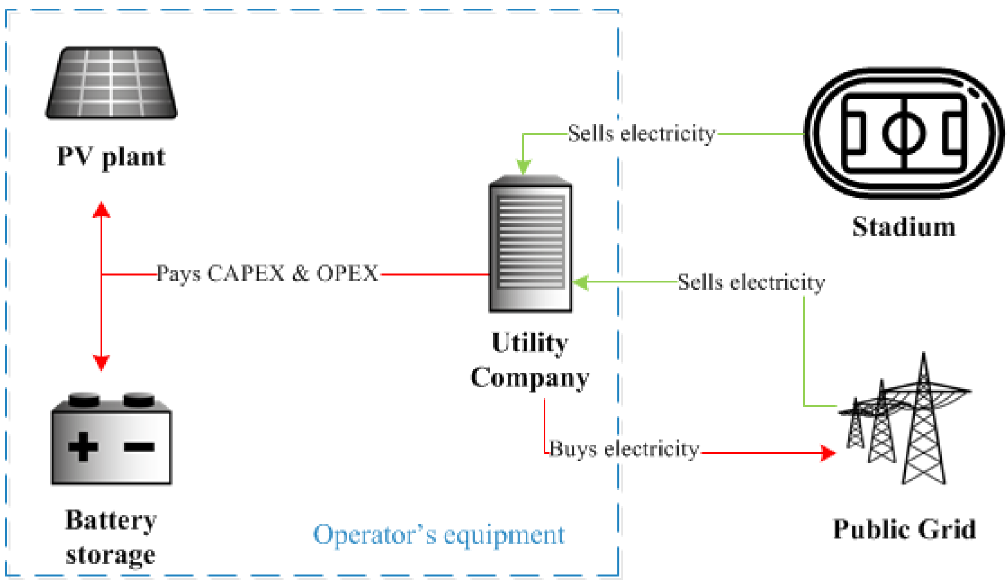

Figure 2.4: Ownership model of the proposed system with a PV plant, battery storage and the grid with a utility company as operator

In order to calculate an economically favourable use of the battery storage but also to compare the economic feasibility of all three systems, the ownership remains with the stadium operator in this thesis for simplification reasons.

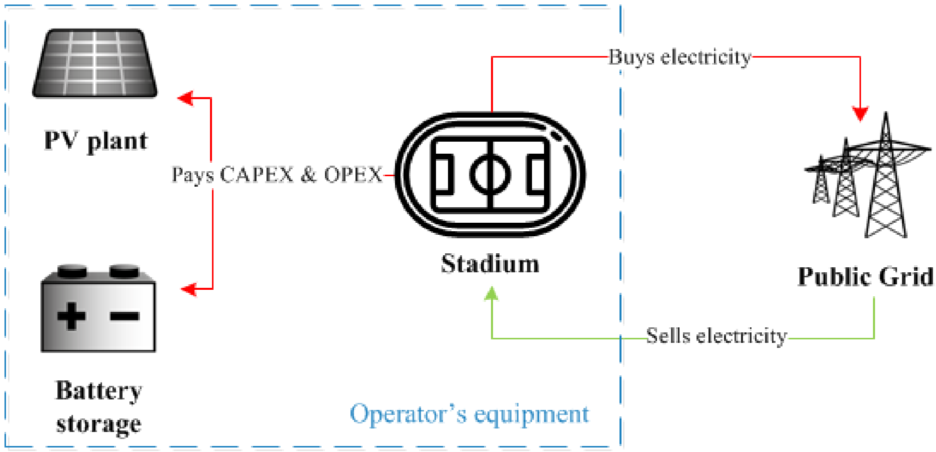

Figure 2.5: Ownership model of the proposed system with a PV plant, battery storage and the grid with the stadium as operator

The economic feasibility for the PVBES system is thus calculated from the stadium operator's perspective who is the owner and operator of the PV plant and the battery storage. This is done in order to simplify the determination the economic feasibility for the new system. In summary, the ownership model and CFs in Figure 2.2 represents the DG system which is described and assessed in Chapter 3. Figure 2.3 shows the ownership and CFs of the PVDG system in Chapter 4. Finally, for the assessment of the PVBES system in Chapter 5.1 and the economic scenarios in Chapter 6, the ownership model considered is the one shown in Figure 2.5.

2.3 Modelling

The modelling and calculations were carried out in energyPRO, although few simpler calculations were done in Microsoft Excel.

2.3.1 Excel

Microsoft Excel is a widely used spreadsheet software [81]. For this thesis it serves as a data collection platform as well as a tool to build the demand model of the stadium which is later fed into energyPRO. Furthermore, interim and final results are collected and diagrams are made to represent the outcome of the calculations graphically.

2.3.2 energyPRO

The modelling software energyPRO was developed in Denmark and enables the user to conduct combined technical and economic analyses of energy projects. RE projects among other can be easily modelled and the economic consequence of technical changes is shown in comprehensive graphs and reports. The reason for this choice is the possibility for a techno-economic analysis which is the key point in this thesis. Advantages are given through the clear user interface, the simulation of different operation strategies and system optimisation of hourly operation. It is widely agreed on the requirement of hourly models for suitable and adequate representation of systems [82]. The software comprises different modules, of which the DESIGN, OPERATION and the FINANCE modules are relevant for this thesis [83]. The DESIGN module is the base module of energyPRO which allows the modelling of an energy system with an unlimited number of units in a maximum time frame of one year. It can analyse the use of storage systems, choose an optimal operation based on electricity prices but with respect to the given demand, whereas the OPERATION module optimises the operational strategy for different units in an energy system. This strategy takes into account expected load demand and price prognosis. Finally, the FINANCE module can be used to make calculations over a longer period of time, in this case 20 years and respects long-term economic effects like inflation and interest. It is applied for example when calculating the net present value (NPV) or net present cost (NPC) of investments [83].

DG system

For the first system, a separate model is made where a DG supplies the game demand. For this, a demand model is built which only includes match days. The remaining demand is covered by electricity from the grid, where the price considered is the average industry electricity price in Germany in 2018.

PVDG system

Similar to the previous method, the results from the model with the DG supplying the game demand is taken and the remaining load is put into a new demand model where the demand supplied by the DG is not represented. This remaining load is fed into a new model with the PVDG system, where the electricity price is again set as for the DG system and a FIT is considered for the excess electricity that is fed into the grid. The same model calculates the potential outcome when buying and selling electricity directly on the spot market by taking German Day-Ahead price data from 2018 for the 20 years of calculation.

PVBES system

For the PVBES system, the model calculates the supply of the stadium with different price indications. Some, like the self-consumption surcharge are calculated beforehand and then indicated in the FINANCE model as a fixed payment for every year. This method has its faults as the production can vary from year to year depending on external conditions, therefore the costs are not constant either. However, given that the same prices, irradiation and temperature data are used for the 20 years of calculation time, this issue can be neglected.

2.4 Economic assessment

The key calculations to be carried out in an economic analysis for a PV project are CFs, the NPV or NPC and, if relevant, the payback time. These calculations give an overview of the profitability and amortisation of an investment and furthermore, the alteration of CFs and the in consequence altered results of the NPV and payback time provide good comparison for the different economic scenarios investigated in Chapters 4, 5 and 6. These methods have also been used in other economic assessments for PV plants [52, 84] with [84] referring to more research in use of this method. Following values are used consistently for all economic calculations:

- Duration of economic calculation n: 20 years
- Time period t: one year
- Nominal interest rate i: 2%
- Inflation rate: 1%

The choice of interest and inflation is described in Section 2.4.3.

2.4.1 Cash Flow

Below are the Equation 2.1 that shows the calculation of the CF done for each time period t where I_t are revenues and E_t the expenditures per time period t.

$$CF = \sum I_t - \sum E_t \tag{2.1}$$

2.4.2 Net Present Value and Net Present Cost

The NPV (Equation 2.2) shows the sum of all the CF within the time frame n. The values depend on various factors like tax rates or the inflation rate in Germany. If the NPV is positive, it shows the profitability of the investment [52]. The investment costs NP_0 are represented in time period $CF_{t=0}$ and a real interest rate i of 3% is applied.

$$NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+i)^t} \tag{2.2}$$

For this thesis, instead of the NPV the NPC is looked at for the three different systems. The NPC represents a negative NPV with a positive value (see Equiation 2.3), and is used for the negative NPV results in Chapters 3, 4 and 5.

$$NPC = -NPV \tag{2.3}$$

For results of the economic scenarios in Chapter 6, both the NPC and the NPV are listed depending on the result, and for comparison, the NPV of the PVBES system's results is shown in the conclusion.

2.4.3 Interest rate and inflation

The calculation of the NPV requires the determination of an interest rate. This has to be chosen carefully as it can have significant impact on the results [44, 85]. In energyPRO, two options can be used, namely the nominal interest rate, which is determined separately from the inflation rate, and the real interest rate, where inflation is considered in the value of the rate. EnergyPRO allows both the input of the inflation rate and the nominal interest rate in the FINANCE module, therefore the two are handled separately. Note that the inflation rate is applied on the CFs directly while the interest rate is included in the NPV or NPC calculation.

The inflation rate indicates the rate with which the value of goods or services are rising or the "worth" of a country's currency is decreasing [86]. Since 2009, the inflation rate in Germany had a fluctuation of between 0.5% and 2% compared to the previous year. For this thesis, an inflation rate of 1% is considered throughout the 20 years.

The interest rate for RE investments in Germany have been decreasing in the past years. While some studies use an interest rate of 5% for the economic assessment and comparison between fossil fuels and RE [87], a much lower interest rate of 1% is used in [18] to compare the LCOE of different kinds of fuels. For economic assessments of battery storage systems supporting a RE plant, interest rate between 4% [85] and 6% [88] are given. In this thesis, the interest rate is set at 2%. Even though the choice of the rate can be considered low compared to the ones mentioned before, one has to keep in mind that the inflation rate is also included, separately, which results in a real interest rate of 3%. Furthermore, the same interest and inflation rate is used in all three system calculations, same as in the research methods mentioned in this paragraph, and is therefore valid for the aim of this thesis which is to provide a comparison between the three systems.

2.5 Data collection and input values

In order to carry out this research, both primary and secondary data was collected. Primary data is essential given that this study refers to a specific case which can only be assessed accurately if real data is used instead of estimations. A significant amount of data is collected from a study of [71] who carried out a preliminary feasibility study of different options for supplying the energy demand of the new stadium. Other data was collected from, complemented by or verified through correspondence with retailers, planners and other experts. A major challenge with obtaining cost data for the components of a PV plant is the fact that retailers are quite reluctant towards giving access to their products' costs. In [44], a similar method for data collection with comparable challenges was carried out, where listed prices from various sources were identified and combined with assumptions which were based on sources that could not be cited in order to preserve the retailer's anonymity.

The quantitative data is essential for analysing the techno-economic feasibility of this case in order to produce a determinate solution which can later be used for conducting further qualitative research. Qualitative data was not collected as it would have surpassed the scope of this thesis. The delimitation of this focus is discussed later in Chapter 7. Secondary data was fundamental for understanding the German regulations for the energy market and how they have affected the development of RE until now. Furthermore, literature research on similar topics were used to gain insight on the state of research, as well as to collect technical data which could not be collected on primary data source terms. The sources and calculations used to determine the technical data, CAPEX, OPEX and other relevant information of each technology (DG, PV, battery) can be found in the Chapters 3, 4 and 5, respectively.

2.5.1 Stadium demand model

Data is taken from [71] who did a preliminary technical assessment for the new stadium and proposed different methods to cover the heat and electricity demand with RE. Based on this assessment, the heat demand was decided to be covered through district heating by the excess heat from a factory located close to the stadium. For this reason, this this thesis only deals with the electricity demand. The annual electricity consumption is estimated to be 1.6 GWh for the new stadium. Furthermore, the monthly electricity demand is given, where it is assumed that electricity demand is especially high in the summer months where cooling is required. Finally, the load profile of a match day is depicted based on measured data from the old stadium, with a peak demand of 950 kWp. Figure 2.6 shows the measurement of the old stadium's electricity consumption from the year 2008.

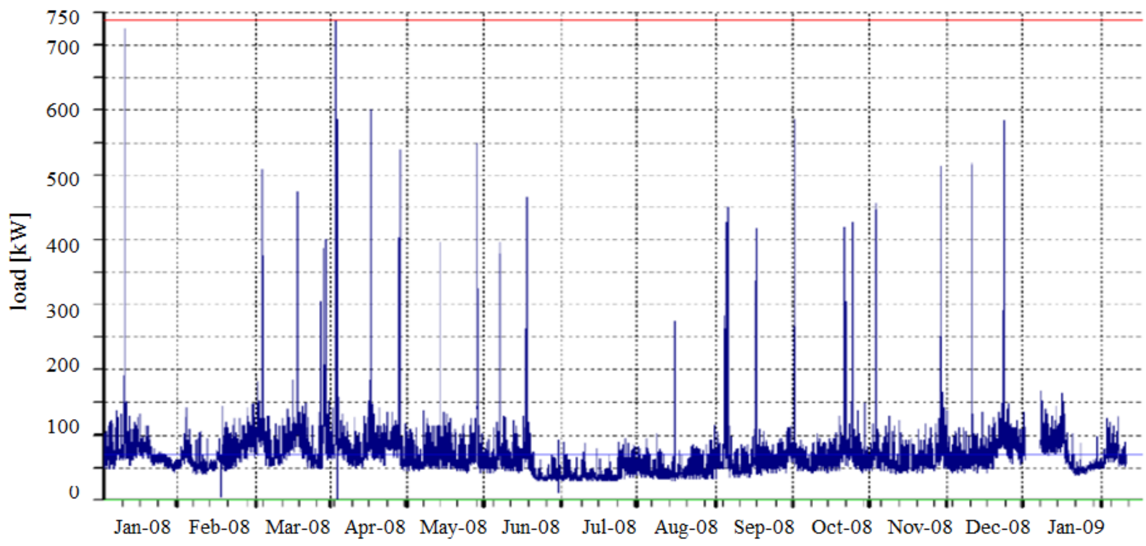

Figure 2.6: Measurements of the consumption during the year 2008 of the old stadium (Schwarzwald-Stadion) in Freiburg (*Modified illustration from [71]*)

Knowing the expected peak demand of the new stadium, which is expected to be up to 1.5 MWp, the load profile of the old stadium was scaled up to match the new stadium's consumption. The electricity load was distributed over 8760 hours, by including match dates from 2018 of the old stadium. It should be kept in mind that these dates vary in the future, however, the number of match is approximately the same. Therefore, even if the day of consumption is not accurate in all the 20 years, this does not affect the total outcome. The resulting annual load modelled for the new stadium is shown in Chapter 3.

2.5.2 Diesel unit

Information about investment costs for the diesel unit were retrieved from retail prices in Germany and from the DEA catalogue to compare.

CAPEX

The CAPEX found for Germany, the DEA price as well as the price difference in % are given in Table 2.1. It shows the CAPEX of 3 different DG sizes in order to provide a more clear comparison of the price differences.

Table 2.1: CAPEX of diesel units (Danish prices from the DEA [89], German prices calculated)

	500 kVA	**1000 kVA**	**2000 kVA**
CAPEX (DEA)	171 500 €	343 000 €	514 500 €
CAPEX (Germany)	112 000 €	192 000 €	320 000 €
price difference	35%	44%	38%

The Danish CAPEX is thus around 35-44% higher for all units, However, Danish prices refer to new units while German prices were retrieved of both new and used units. The DEA notes that prices can vary with about ±20% in 2020. For this thesis, 80% of the Danish price is used, which results in 411 600 € CAPEX, which takes into account the 20% divergence as well as the lower prices in Germany.

Fixed OPEX

The fixed OPEX, mainly maintenance costs, are taken from the DEA catalogue. Since no official maintenance prices were found for Germany, the DEA's cost is scaled down with the factor taken from the price difference factor used for the CAPEX which is -20%. This method is far from optimal as CAPEX and OPEX for DG systems are not in linear correlation to each other. However, given that CAPEX and OPEX of the PV and PVBES system are handled as lineraly interdependent as well, the method is deemed sufficient for this thesis.

Fuel price

Diesel prices are taken from [90] which are available from 1950 - 2018, see Figure 2.7. The fuel prices calculated with are determined by taking the historical diesel prices in Germany between 2000 and 2018 (indicated in Figure 2.7 by the black box) and calculating the linear growth. The reason for choosing this time span is the fact that prices have been constantly growing since 1950 but have experienced high fluctuations from 2000 onward.

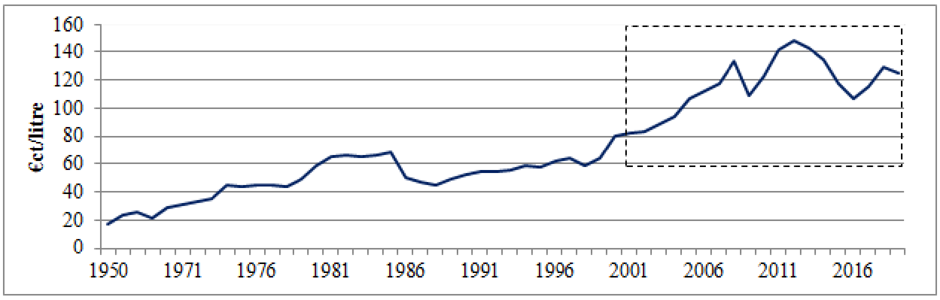

Figure 2.7: Historical price development of wholesale diesel prices in Germany, 1950-2019 (*Own illustration with data from Federal statistical office Germany [90]*)

In comparison, a diesel price forecast for Denmark was published as well in [91]. In order to calculate the future diesel prices until 2037, the linear growth of the two data is identified, both shown in Figure 2.8. Historic linear forecast for Germany is further referred to as *Case 1*, the forecast until 2030 for Denmark is referred to as *Case 2*.

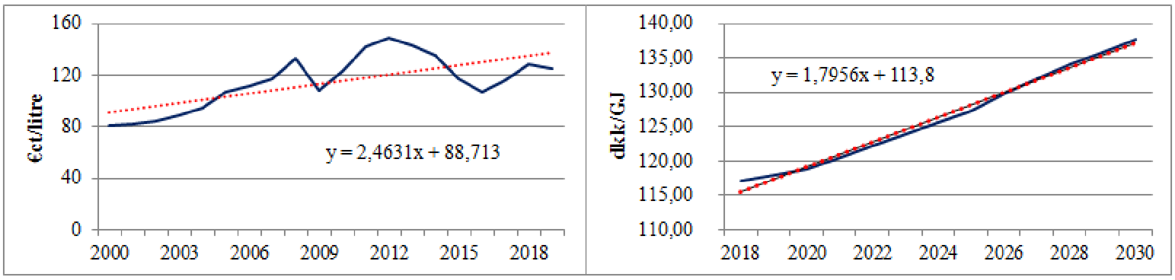

Figure 2.8: Left: German historic diesel prices and the linear growth (Case 1); right: Danish price forecast for diesel and the linear growth (Case 2) (*Own illustration with data from [90] and [91]*)

It can be understood that the price is believed to grow steadily in the following years; indeed, the Danish price forecast assumes a 15% growth between 2018 and 2030. In comparison, the price forecast applied from German historic diesel prices assume a growth of only 8% between the same time span (2018 - 2030). The linear growth of both predictions is applied to German prices of 2019 and then calculated. Equation 2.4 shows the formula from Case 1 used to calculate the diesel prices between 2020 and 2037:

$$y = 2,4631x + 124,8 \tag{2.4}$$

The Danish forecast (Case 2) is applied through Equation 2.4 for the years 2020 - 2037:

$$y = 1,7956x + 124,8 \tag{2.5}$$

Value y is the diesel price identified, while x is the number of years passed since 2018, the first year of the calculation. For the year 2019, the actual price is taken (124.8 €ct/litre), the prices of the following years are calculated. Furthermore, the tax for diesel fuel (47.04 €ct/litre in Germany [92]) is added. Taking the linear growth to assume future prices has strong limitations due to its simplicity and the dependence on other factors like geopolitical situations, extreme climate conditions impeding production or financial crises, all of which have strongly influenced diesel prices in the past [90].

The annual fuel consumption, as well as total fuel costs and emissions are calculated by energyPRO. The NPC is calculated by inserting all data related to the diesel unit, fuel consumption, CFs, electricity demand during the game times, as well as interest and inflation rate. Diesel price data is required from energyPRO in monthly values, therefore the calculated annual diesel prices were divided by 12 without taking monthly fluctuations into account.

2.5.3 PV plant

The capacity of the rooftop plant was determined in the study of [71] and resulted in a potential size of 1.8 MW. Higher capacities are not possible due to aesthetic reasons and limited rooftop area [71]. However, different PV plant sizes are calculated with in the analysis in Section 5.3.3. Other input data required to calculate the electricity production in energyPRO is taken from the data sheet from [93].

CAPEX

The investment cost for the PV plant in this thesis is determined by combining information from literature research, PVDG system planners and own calculations in order to present an accurate and up-to-date investment cost. From literature sources, it was found that most price data refer to residential or commercial scale PV plants up to 500 kWp. Given the economy-of-scale effect, the price per unit and therefore the overall investment cost can vary significantly depending on the size of the plant. Figure 2.9 shows the costs per kWp for different capacities and the degression line. Note that these prices are applicable only for rooftop systems.

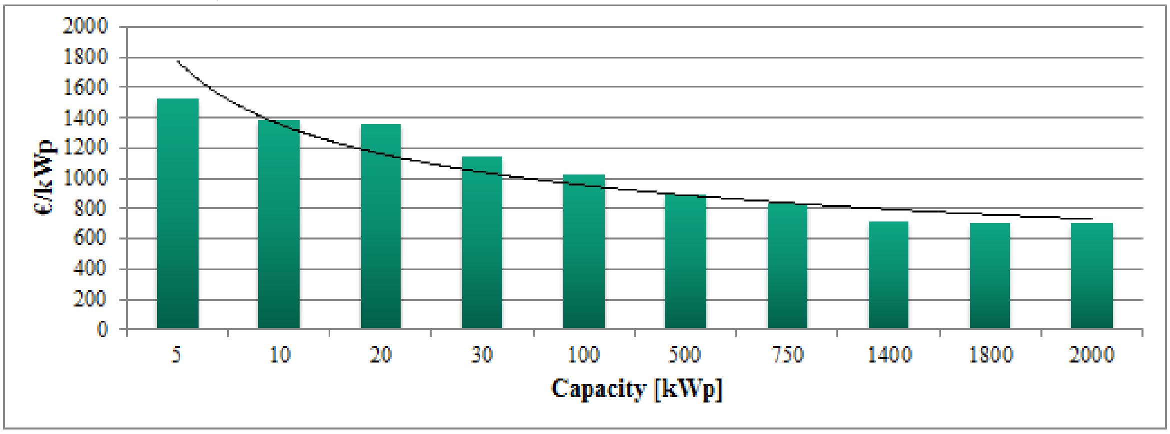

Figure 2.9: Rooftop PV system price in Germany 5-2000 kWp (*Own illustration with data from Fraunhofer ISE [9] and own calculations*)

It can be seen that until 500 kWp there is an evident economy-of-scale effect, while above 500 kWp the effect decreases.

OPEX

OPEX for the PV plant can be calculated by assuming 1-2.5% (1% [9], 1.5% [94] or 2.5% [16]) of the total investment costs to be the annual OPEX.

2.5.4 Battery

The choice of battery technology is carried out by identifying the most common battery technologies for this scale and listing their characteristics. This is done through extensive literature research and discussions with experts from the field. The main requirements for the stadium are taken as general requirements for the PVBES system and by listing the main characteristics, the battery technology is chosen according to these requirements.

CAPEX

The CAPEX of the battery is determined by taking an anonymous offer from a retailer, given the technical requirements which are listen in 5.

OPEX

OPEX for the battery are calculated similar to the PV plant, by taking 2% of the investment costs for the annual OPEX, following the example of other studies [95, 96]. Different sizes and thus CAPEX and OPEX are considered in the sensitivity analysis of the PVBES system in Section 5.3.3.

2.5.5 Electricity market data and other external conditions

Market data for the year 2018 is retrieved from the Bundesnetzagentur (Federal Network Agency Germany) [29] and reformatted in order to comply with the formatting requirement of energyPRO. Hourly temperature and irradiance data are retrieved from energyPRO, where weather data is available for example from the Climate Forecast System Reanalysis 2 (CFSR2). This source was chosen as the location of the measurements is located closest to the stadium area. Note that this data is considered for all 20 years of calculation. Therefore, effects like climate change and global warming over the next years are not taken into account.

2.6 Economic scenarios

For additional income, other means of generating revenues with the RE system are examined. For instance, the CFs from selling electricity on the balancing market are looked at. Furthermore, possibilities for direct selling are investigated by considering selling excess electricity to a nearby student residence a trade fair facility and to EV charging stations. For examining the results, the amount of electricity fed into the grid from the PVBES system is determined. Then, the different electricity prices are identified for the various scenarios and a price is set which would make the purchase directly from the stadium (economically) more favourable. The NPC is then calculated by changing the CFs in the FINANCE model and looking at the summary and key financial figures.

For electricity trading on the energy market in Germany a monitoring and control unit is required, which makes it possible to manage the power plant externally through wireless connection. This is connected to an investment of between 70-550 € and a monthly fee of 2-10 € [97] of which both are considered to be included in the CAPEX and OPEX. The following sections describe which market strategies are used for the calculations.

2.6.1 Spot market trading

Trading on the electricity spot market is carried out on the Day-Ahead market for these calculations. The calculation of revenues and expenses is carried out with historic price data from 2018 and used for the next 20 years, with an average price of 44 €/MWh. This implies that prices are known and operation strategies (charging and discharging of battery according to market price) are optimised accordingly. It should be kept in mind that these prices can never be known completely in advance which is why the resulting CFs are not entirely accurate. In order to give a more precise idea of future CFs when trading on the balancing or spot market, accurate forecasting has to be applied and possible deviations need to be assumed. Nevertheless, as the same price data and calculation method is used for the comparison of the PV and PVBES systems, the representative results give a good idea about the economic feasibility of the trading possibilities.

2.6.2 Market premium

The market premium scheme is a model that ensures the remuneration of RE power plant operators who are trading electricity on the spot market when prices are low. It guarantees a minimum income even at low spot market prices and additional income is then created when market prices are high. In this thesis, the market premium is represented in the combination of both FIT and spot market trading which is calculated for both the PVDG system and the PVBES system. This means that if spot market prices are low, a fixed premium is still paid to the operator. This is achieved by adding two time series into the energyPRO model where one represents the normal spot market prices and the other replaces values lower than the market premium with the market premium. This way, expenses are calculated with regular spot market trading prices while the income is calculated by respecting the market premium in case spot market prices are lower.

The market premium varies on a monthly basis and in 2018 until mid-2019, it has diverged between 30 and 60 €/MWh [33]. This variation is not taken into account in the thesis' calculations, but rather a fixed premium of 45 €/MWh is set for the duration of the considered 20 years. Again, the same value is used for comparing the different systems, therefore, in order to compare the results to one another the inaccuracy of the method can be neglected.

2.6.3 Balancing market trade

For the balancing market, a specific amount of power is "reserved" and can be used to maintain grid stability. This reserved power is offered on a weekly basis and remunerated by a specific amount of money. In 2019, the demand for balancing power in Germany was around 605 MW [98]. In the calculation carried out in Chapter 6, 1 MW is offered for the week, which is the minimum load for being able to participate in the trading. In order to represent this additional load, the demand model is adjusted by adding 1 MW distributed evenly for every week without a match (34 in one year). For weeks without a match the money is received for 1 MW of reserved power. This method has its limitations since a fixed remuneration is considered in the calculations even though prices vary on a monthly basis. Therefore, rather than adding the monthly variations to the calculation, a high and a low price scenario are considered instead in order to point out the economic potential of balance market trading during high and during lower prices.

2.6.4 Student residence

By identifying the electricity demand of different consumers around the area of the battery storage, the option of selling electricity directly to the user is given. It is not expected that enough excess electricity can be provided to cover the whole demand of the different consumers. Therefore, revenues from direct selling are calculated by multiplying the excess electricity measured with the electricity price the respective consumer would otherwise pay, and a newly proposed price which would make the purchase favourable for the consumer but also not result in too high losses for the operator of the battery. These PPAs offer a new option for consumers to buy their electricity from different providers while ensuring to the operator that the expected revenues are gained. Selling prices are taken into account by considering the electricity price of 2019 for households which were retrieved from [27].

The expenses with PPAs include the EEG surcharge, which is to be paid for every kWh of transferred electricity, and the network charge, as no new transmission wires are considered to be installed for the PPA. The EEG surcharge for 2019 is set to 6.4 €ct/kWh and is used for the duration of the total calculation (20 years). The same accounts for the network charge, which for private household consumers is 2.38 €ct/kWh and for EV charging, 2.65 €ct/kWh, respectively, as of 2019 [12].

Limitations to this method include the risk of not being able to set a PPA with any customer as for this thesis it is assumed that the agreement is set for the course of 20 years. In common practice, most PPAs are set for a time-span of 10-15 years [99] although 20 years are possible as well. The limitation and potential of PPAs is discussed in Chapter 7.

2.6.5 Park&Ride and EV charging

For EV charging stations it is more difficult to determine a price as different charging station operators have different tariffs. Table 2.2 shows some of the prices for charging stations from retailers which can be found in Freiburg. Note that most tariffs differ between AC and

DC charging, where prices for DC charging are usually around 10 €ct/kWh higher. Furthermore, many prices are not counted per kWh as the stations do not yet have a metering system which only became mandatory from 2018 onwards [100]. For this thesis, prices are shown in €/kWh.

Table 2.2: Examples of end-prices from EV charger operators available in the area including taxes (*SOURCE: [100]*)

Charging station operator	AC charging tariff	DC charging tariff	Membership fee
ADAC [1]	0.29 €/kWh	0.39 €/kWh	no
EnBW [2]	0.39 €/kWh	0.49 €/kWh	no
EnBW frequent user	0.29 €/kWh	0.39 €/kWh	4.99 €/month
innogy basic	0.30 €/kWh	6.95 €/charging	4.95 €
innogy direct	0.39 €/kWh	7.95 €/charging	no

It can be seen that prices can vary strongly, mostly depending on the different tariff schemes. Factors like additional membership fees, electricity supply of operator and therefore electricity prices and charging types (AC or DC) play an important role [100]. For this thesis revenues are created by assuming that charging stations are located next to the stadium in the parking area but are owned and operated by another entity than the stadium operator. Income for the stadium owner is achieved by selling the electricity to the charging station operator at a price of 0.40 €/kWh. That leaves a small income margin for the charging station operator, however, the space rental fees are considered to be included. This way, the charging station operator has lower losses when less customers are charging their EVs. The park&ride option is for free just like other park&ride facilities in Freiburg [101] in order to ensure competitiveness. Fees for regulative measures are not taken into account in this calculation, therefore, the outcome is to be viewed as an optimistic scenario.

As for the yearly demand of the charging station, assumptions are made by taking the data from [102]. According to this study, the average charging time for different types of vehicles are between 2 and 8 hours. If 8 hours are considered for slow charging (11-22 kW [103]) and 2 for fast charging (150 kW [103]), it is assumed that in one day. at least one EV is charged for 8 hours with a 22 kW charger and one EV with a 150 kW charger. This would result in a daily demand of 476 kWh and, if multiplied by 350 and thus disregarding most of the match days, an annual demand of 166.6 MWh. Note that these assumptions are not based on average consumption data but rather a minimum assumed demand for the park&ride facility. Therefore, the results should be evaluated critically.

[1] German vehicle association
[2] Energie Baden-Württemberg - German energy provider

3 | Diesel Generator System

This Chapter describes the chosen case which is the new stadium in Freiburg, Germany. Then, the current system (DG system) is described with the chosen input values and calculated performance. After determining the CAPEX and OPEX the NPC is calculated with different factors. Following the economic assessment, a brief estimation of the emissions caused by the diesel unit is given as well, in addition of a proposed CO_2 tax. Finally, the results of all scenarios are presented.

3.1 The stadium in Freiburg

The construction of the stadium began in early 2019 and is planned to be finished by summer 2020 [34]. The new stadium is supposed to replace its predecessor, the old stadium of Freiburg, by offering a larger visitor capacity in the industrial area of the city. Table 3.1 contains facts of the new stadium and compares it to the old stadium in Freiburg. This is also helpful since some data for the new stadium used in this thesis is scaled up based on data from the old one.

Table 3.1: Facts about the new stadium (Wolfswinkel-Stadion) compared to the old stadium (Schwarzwald-Stadion) (*SOURCE: [34, 71]*)

	New Stadium (Wolfswinkel-Stadion)	**Old stadium (Schwarzwald-Stadion)**
Opening year	2020	1954
Visitor capacity	34 700	24 000
Electricity consumption per year	1 600 MWh	839 MWh
Peak electricity demand	1 500 kW	950 kW
Heat consumption per year [1]	2 250 MWh (1 500 MWh - 3 000 MWh)[2]	900 MWh (400 MWh - 1 500 MWh)

It can be seen that both the electricity and heat consumption of the new stadium are around twice the amount compared to the old stadium. The huge difference could be explained by the larger capacity and consequently higher number of snack bars, restaurants, heating and cooling demand, and other loads.

3.1.1 Stadium load profile

In contrast to household or office load profiles, where the daily load differs depending on factors like weekdays, weekends or holidays, event buildings like sport stadiums have electricity load profiles that show strong fluctuations during times when an event is taking place. Figures 3.1 and 2.6 show the load profile of one week in April of an average household in Germany in 2017 (top, green line) [104] and the new stadium with a game day (bottom, blue line).

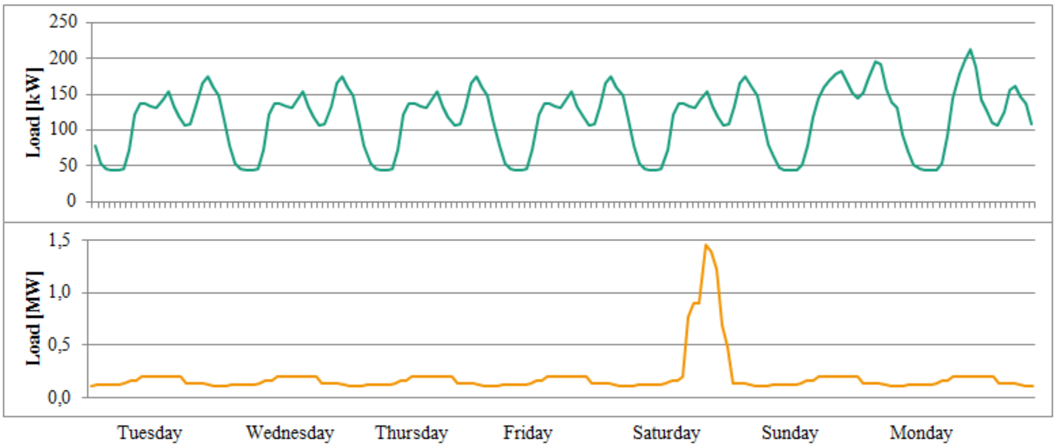

Figure 3.1: Load profile of an average household in Germany (top, green line) and of the stadium in a week with a game day in April (bottom, blue line) (*Own illustration, data from [71, 104]*)

Figure 3.2 below shows the yearly electricity load of the new stadium.

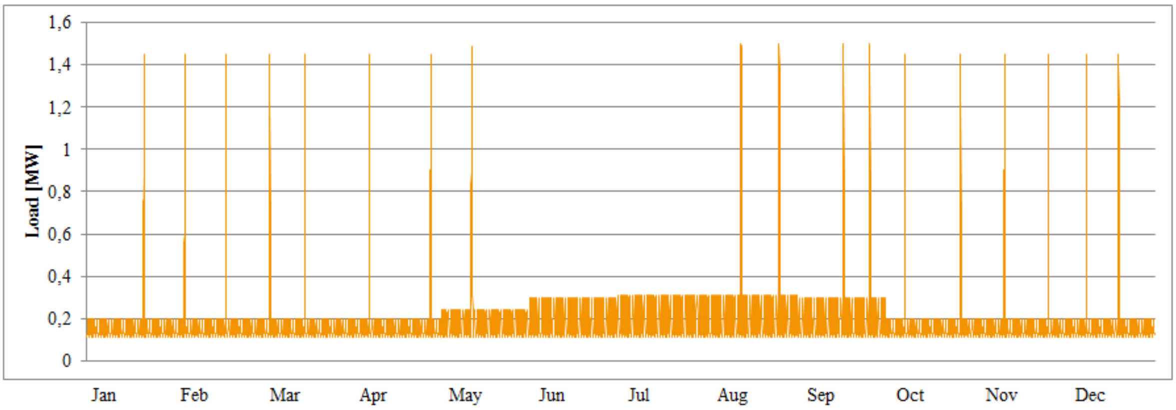

Figure 3.2: Estimated modelled electricity load of the new stadium in one year (*own illustration and assumption based on data from [71]*)

3.2 System description

In general, stadium operators use diesel generators for peak shaving for event days. This is done in order to ensure a security of supply in the event of a power outage, but also in order to lower the electricity expenses during the peak demand, as peak consumption rates can increase the electricity prices for the consumer. This load is mainly represented by television broadcast appliances and lighting, but also kitchen activities and cooling of beverages to name a few [71]. The advantages of DGs are high reliability, fast response time, minimal impact on performance through ambient conditions and low investment costs. However, the overall efficiency is deemed low compared to other alternatives. Furthermore, with diesel being one of the most polluting sources of electricity, the air pollution caused by the generator's operation is a significant disadvantage [89, 105]. Furthermore, the environmental advantages of RE which represent around 47% of the total electricity production in Germany in 2019 [41], are not exploited.

3.2.1 Electricity supply from the grid and DG

The match is supplied entirely by a 2000 kVA DG, of which a data sheet [106] is taken to calculate the technical performance. The heat value of diesel (usually between 42-46 MJ/kg) used in energyPRO is set to 43 MJ/kg [107]. Investment costs are calculated by comparing different market prices and defining an average. Diesel price data for Germany was retrieved from [90], and future prices as well as the overall OPEX were taken from the DEA [89]. These parameters as well as information from the data sheet [106] are fed into the models as previously described in Chapter 2.

3.2.2 Electricity production

Table 3.2 shows the general input parameters and output values which apply for the operation of the DG.

Table 3.2: Input data from [106, 107] and energy production and operation data from DG calculated by energyPRO

Variable	Value
DG standby rating	1 600 kW
Heat value diesel	43 MJ/kg
Operating hours	72 h/year
self-reliance	6%
Annual electricity production	90 MWh
Annual fuel consumption	9 404 kg

Figure 3.3 shows the supply of the consumption during a game supplied by the DG.

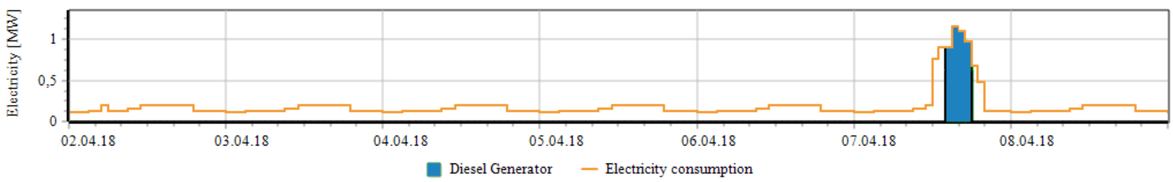

Figure 3.3: Electricity load of the stadium in one week with a match with DG covering 4 hours, April 2018 (*own illustration from energyPRO*)

As it can be seen, the load curve shows a sharp growth of the electricity consumption shortly before the start of the game, which is at 15:30 pm. This gradual increase is explained by the systematic addition of consuming appliances like for example to supply media equipment, additional lighting, kitchens, and other devices. The peak load occurs 15 minutes before the start, at 15:15 pm and decreases after approximately 4 hours.

3.3 Economic assessment

Unlike with RE power plants, fossil fuel powered units have higher OPEX than CAPEX. This is mainly due to fuel and maintenance costs. In this section, the economic calculations are carried out by investigating the CAPEX as well as the OPEX of diesel units, which later serve as input data for the NPC calculation. In order to have a financial comparison between the two systems, the time frame for this calculation is set for 20 years (in accordance with the expected average lifetime of PV modules), even though diesel units can have a lifetime of around 25 years [89].

3.3.1 CAPEX diesel unit

The CAPEX are calculated in two ways, first by taking data from the Danish Energy Agency's (DEA) catalogue, where average costs for diesel units are given. Furthermore, in an extensive online research, various retail prices from Germany were found for the DG which were used to identify an average price. Note that the CAPEX given only relate to the diesel unit and does not take into account transportation costs.

3.3.2 OPEX diesel unit

Fixed OPEX are taken from the DEA catalogue, while [90] provided diesel retail prices in Germany, to which a future price development is estimated and applied as described in Section 2.5.2. It is assumed that diesel prices will experience an overall growth, as both the historic diesel prices in Germany and the diesel price forecast from Denmark show. Figure 2.8 shows the calculated diesel prices with the historic data prediction approach (further referred to as Case 1 - left) and the price growth estimation from the DEA [89] applied to German diesel prices (referred to as Case 2 - right):

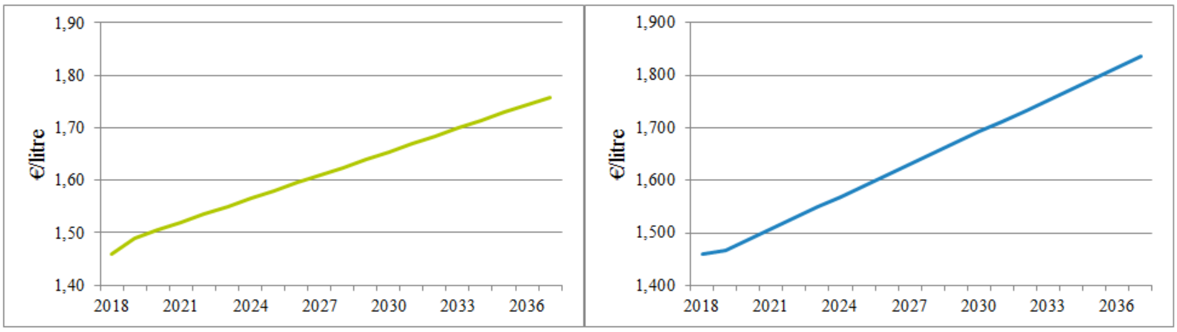

Figure 3.4: Diesel price forecast Case 1 (left) and Case 2 (right), 2018 - 2037 (*own illustration and calculation based on data from [90] and [91]*)

These values already contain the wholesale price of diesel as well as taxes, which make up around 60% of the retail price, and import costs [92]. It can be seen that both approaches assume an overall growth of the diesel price in the following years. The resulting annual variable OPEX are shown in Table 3.5 in Section 3.3.5.

3.3.3 Electricity bill

The electricity demand of the stadium (excluding the peak shave by the DG) is covered by electricity from the grid. Given that only 6% of the total yearly consumption are covered by the DG, the remaining electricity is bought from the grid. Table 3.3 shows the input values for calculating the additional costs for purchasing electricity.

Table 3.3: Calculation of the annual electricity bill for the stadium

Variable	Value
Total annual load stadium	1 609 MWh
Annual load covered by DG	90 MWh
Annual remaining load covered by grid	1519 MWh
Electricity price industry 2018[3] [27]	197.7 €/MWh
Annual cost of purchased electricity	300 108 €
Self-consumption surcharge	60.5 €/MWh
Annual surcharge for self-consumption	5 445 €
Annual grid electricity cost	305 553 €

3.3.4 Emissions

Despite the declaration of various climate goals that include the decarbonization of the electricity sector in Germany, there are no effective incentives like CO_2 taxes in place yet. Currently, the CO_2 certificate trading system allows companies to emit 1 ton of CO_2 per certificate, which are annually distributed among utilities and companies. Depending on the amount of higher or lower emissions than allowed, companies can buy or sell certificates. Problems in the system are for example that certificates are less expensive than the investment into RE, therefore it is not enough to effectively support the expansion of renewables [5]. However, suggestions have already been made by the Environmental Agency to start with a 30 €/tCO_2e[4] tax for utility and industry [5] which is eventually increased to 180 €/tCO_2e. The 30 €/tCO_2e suggestion is applied to calculate future OPEX of the DG system, with an annual increase of around 10% until 180 €/tCO_2e is reached in 2020. Table 3.4 shows the calculated CO_2 and CO_2e emissions for the DG and the tax for 2018 and 2037, respectively.

Table 3.4: Diesel emission factors [108], annual CO_2 and CO_2e emissions and proposed CO_2e tax as recommended in [5] + results

Variable	Value
CO_2 [108]	3.16 kgCO_2/kg
CO_2e [108]	3.21 kgCO_2/kg
Annual fuel consumption	9 404 kg
total CO_2 emissions	30 tCO_2e/year
CO_2 emission tax	30 - 180 €/tCO_2
tax increase per year	10%
total CO_2 tax costs 2018	900 €
total CO_2 tax costs 2037	5 504 €

3.3.5 Total CAPEX and OPEX

Table 3.5 shows the annual fixed and variable expenses for both units, and the average total OPEX in one year.

[4] CO_2e - CO_2 equivalent including CO_2 and other GHG emissions

Table 3.5: Input values of the calculations for the economic assessment

Variable	Values	
CAPEX	411 600 €	
Annual cost of purchased electricity	305 553 €	
Annual fixed OPEX	14 080€	
Fuel costs 2018	9 308€	
	Case 1	**Case 2**
Fuel costs 2037	14 062 €	14 756 €
Annual CO_2 tax	900 - 5 504€	
Total OPEX 2037 (no CO_2 tax)	399 478 €	400 136 €
Total OPEX 2037 (with CO_2 tax)	404 878 €	405 536 €

3.4 Results and conclusion

The NPC is calculated for the DG, with both price development prognoses (Case 1 and Case 2). This system however only results in economic loss as no revenues are gained if the money saved from operating the DG instead of purchasing electricity from the grid are neglected. Table 3.6 lists the final CAPEX and OPEX values and the results of the NPC calculations for both cases without and with the inclusion of the CO_2 tax.

Table 3.6: Main input parameters and results of the NPC for the DG system calculated over 20 years

Variable	Case 1	Case 2
Net CF 2037 (no CO_2 tax)	- 405 783 €	- 406 533 €
Net CF 2037 (with CO_2 tax)	- 411 288 €	- 412 037 €
NPC (no CO_2 tax)	7 779 211 €	7 782 863 €
NPC (with CO_2 tax)	7 830 758 €	7 834 410 €

When comparing the results from the two different diesel price prognosis methods (Case 1 and Case 2) it can be observed that the price difference between the two NPCs is quite small. This is because the annual fuel costs or variable OPEX take up only around 2.82% in 2018, 4.21% or 4.41% in 2037 respectively, depending on the diesel price growth. The CO_2 tax does not add significant economic disadvantage either as it only makes around 0.2% of the total expenses. A break-down of the expenses from the year 2018 can be seen in Figure 3.5.

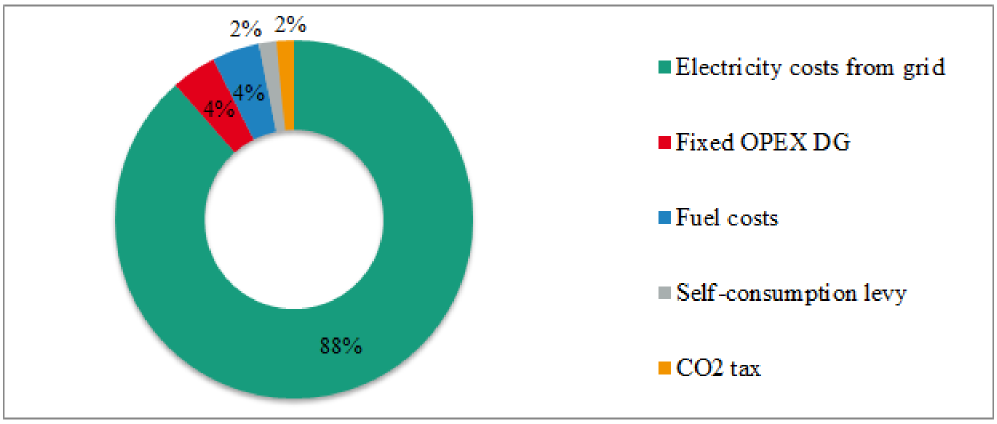

Figure 3.5: OPEX breakdown DG system (*own illustration and calculations*)

For sensitivity, the higher CO_2 tax proposition is applied, where in 2018 the tax starts at 180 €/tCO_2e and grows by 10% every year, as in the previous calculation. This would mean yearly expenses of between 5 400 and 33 000 € for the tax. The results of the NPC with new taxes is shown in Table 3.7.

Table 3.7: NPC results for both Case 1 and Case 2 with higher CO_2 tax

Variable	Case 1	Case 2
NPC (no CO_2 tax)	7 779 211 €	7 782 863 €
NPC (low CO_2 tax)	7 830 758 €	7 834 410 €
NPC (high CO_2 tax)	8 088 496 €	8 092 148 €

The NPC results are shown for comparison in the graph of Figure 3.6 with orange representing Case 1 and red representing Case 2 results.

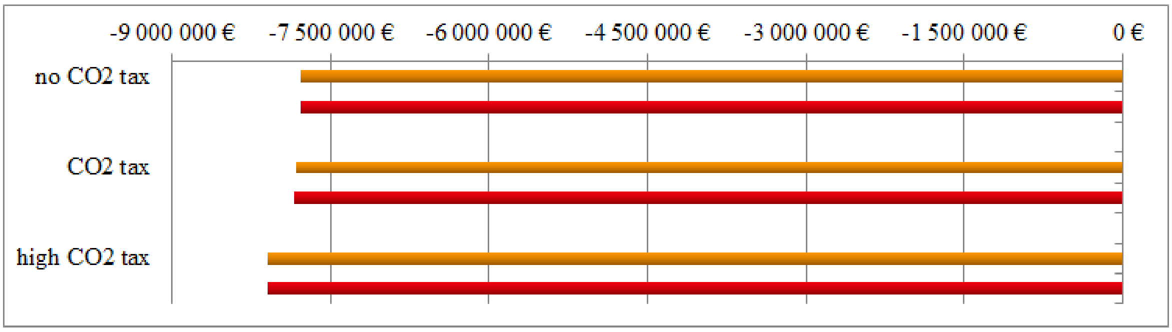

Figure 3.6: NPC results DG system (orange - Case 1 results, red - Case 2 results) (*own illustration and calculations*)

Taking all the expenses to cover the electricity demand of the stadium in 20 years, the total cost is between 7 and 8 million €. Considering that no revenues are created with this system, both the PVDG system and the PVBES system can potentially represent a more favourable economic scenario to the stadium operator as excess electricity from the PV plant can be sold.

4 | Photovoltaic and Diesel Generator system

In this system, the electricity demand of the stadium is to be covered by solar power and the grid when no match takes place. Like in the previous Chapter, the DG operates only during match to ensure security of supply. Later Sections show the input and results of the economic assessment.

4.1 System description

Figure 4.1 represents the system where the DG supplies the game load as determined previously in Chapter 3, and a PV plant supports the remaining (base) load. Note that Figure 4.1 only shows a representative model.

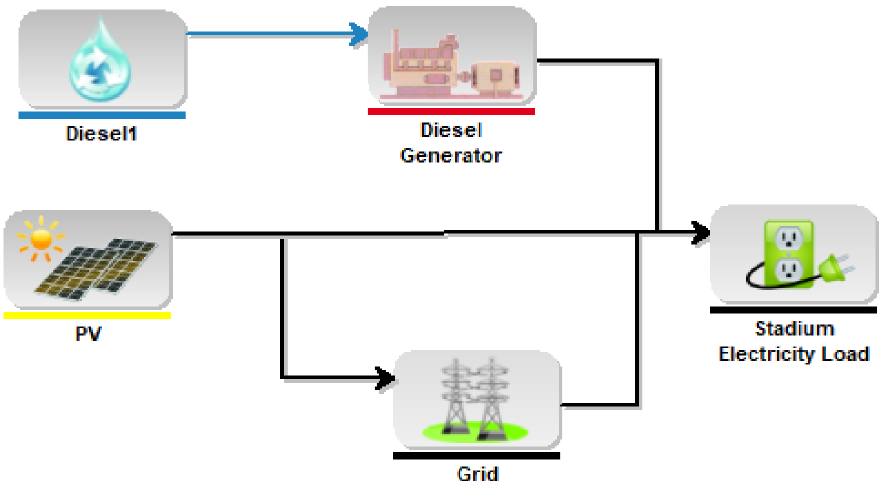

Figure 4.1: Graphical representation of the PVDG system (*own illustration from energyPRO*)

Excess electricity produced by the PV plant can be sold to the grid in order to generate income. This CF is also considered in the later Section where the NPC for the system is determined.

4.1.1 Electricity supply with PV and DG

In order to calculate the electricity production from the PV plant, various input parameters are required, most of which are given by data sheets from the specific modules. For this thesis, the PHOTON SOLAR SC-LINE 310 W module is chosen [93].

Global irradiation is measured over a year and includes both direct and diffuse solar radiation, as both influence the electricity production of PV. The irradiance is the solar energy that reaches a horizontal area of one m^2. The output power of the PV plant depends on factors like irradiance but also module shading, inclination on the horizontal plane, deviation from south and the ambient temperature [89]. Figure 4.2 shows the monthly average ambient temperature (left) and the monthly average irradiance (right) of the data that was used in the calculation.

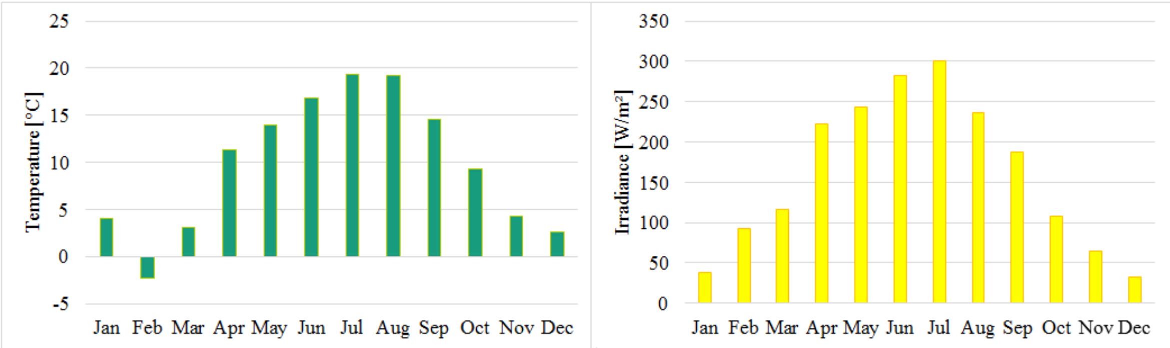

Figure 4.2: Average ambient temperature (left) and solar irradiance (right) in Freiburg (*own illustration, data from [109, 110]*)

Since the PV panels are mounted flat on the rooftop and no high constructions are located within relevant distance to the stadium, the effects of shading are not taken into account. The 5° inclination is the sloping roof of the stadium, and remains the inclination calculated with as modules may not be oriented optimally in order to achieve the maximum possible production output, due to a restriction given by the stadium operator. In comparison, an optimal inclination and deviation in the area would be 34°and 0°, respectively [110]. No data could be retrieved on the exact position of the stadium regarding the cardinal points, therefore a value (90°) is chosen which provides a semi-optimal electricity output. The peak power P_p represents the maximum power output of the module that can be achieved with standard testing conditions (STC)[1]. The nominal operating cell temperature (NOCT) is defined for every module type in STC and helps to calculate the operating cell temperature at the given conditions like irradiance and ambient temperature of the location of the modules. Table 4.1 shows relevant data required for calculating the electricity production of the PV plant.

Table 4.1: Input values for the calculation of the PV electricity production

Variable	**Value**
PV plant peak capacity C_p	1.8 MW
Inclination [71]	5°
Deviation	90°
Peak power P_p per module [93]	310 Wp
Temperature coefficient of power [93]	-0.400 %/°C
NOCT [93]	45°C
Aggregated Losses from module to grid [93]	5%
Number of PV modules	5 608

[1]STC - Irradiance: 1000 W/m^2, cell temperature: 25°C[93]

4.1.2 Electricity production

During a match, the 90 MWh load is supplied by the DGs. From the PV plant, 846 MWh per year can power the stadium directly while the remaining load is supplied by electricity purchased from the grid. The results of the system's electricity production and other output values are shown in Table 4.2.

Table 4.2: Energy production and operation data from DG calculated by energyPRO

Variable	Value
Annual total load	1 609 MWh
Annual electricity production DG	90 MWh
Operating hours DG	72 h/year
Annual fuel consumption DG	8 245 kg
Annual electricity production PV	2 453 MWh
Electricity covering stadium load PV	846 MWh
self-reliance with the PVDG system	58%
Operating hours PV	4 749 h/year

Figure 4.3 shows a match week in April with the orange line representing the stadium load, yellow showing the PV production and the blue area supplying the game load.

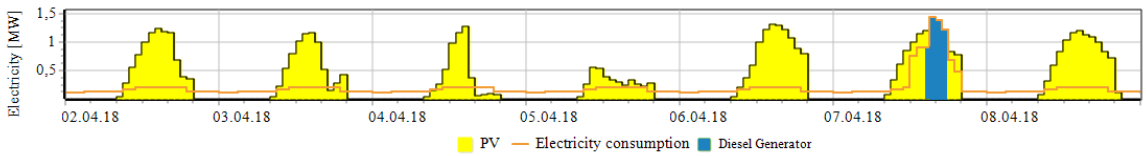

Figure 4.3: Load and supply of the stadium in April 2018 with a DG and a PV plant covering 58% of the stadium load annually (*own illustration from energyPRO*)

The electricity flows between the units, the stadium and the electricity market is shown in Figure 4.4.

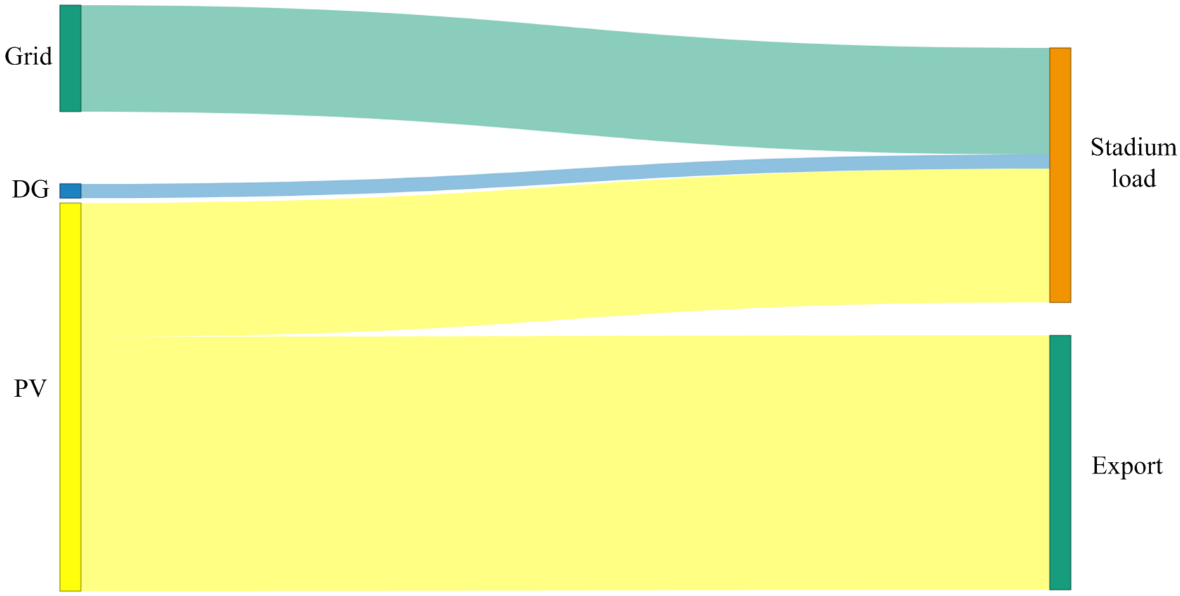

Figure 4.4: Sankey diagram of the energy flows covering the stadium load and being exported from the PVDG system (*own illustration and calculations*)

As only around 34% of the electricity produced by the PV plant can be used to power the stadium's base load, the rest is fed into the grid, or sold at the electricity market.

4.2 Economic assessment

For the economic assessment, the stadium operator is still considered as the owner of the power plants and therefore bears all expenses including CAPEX, OPEX and expenses for buying electricity to cover the demand that cannot be supplied by solar power. The determined CAPEX and OPEX are shown in Table 4.3.

Table 4.3: Determined CAPEX and OPEX for 1.8 MW PV plant

Variable	Value
CAPEX PV	1 260 000 €
Price per kWp	700 €
OPEX PV	18 900 €
OPEX: amount of investment cost	1.5%

4.2.1 CAPEX PV plant

Research has shown that in the planning area, PV is often discredited due to high investment costs. This is also due to the fact that the prices used for the calculation date back to an earlier time, despite the constantly decreasing costs. Therefore, price predictions are often determined to be higher than the actual current costs [18]. This phenomenon is also observed when looking at the price prediction of the preliminary study for the energy supply of the stadium, in [71]; the investment costs for a 1.8 MW PV plant are determined to be 2.3 million € (it should be kept in mind that the study of [71] was published in 2015), when calculated with 1 300 €/kWp. This is almost double the price per kWp considered in this thesis, even though 700 €/kWp for this plant size are more accurate according to a retailer and experts. This economy-of-scale effect can be observed for example in the cost analysis of [21], where the price per kW is compared with different PV plant sizes. This occurs because fixed costs like planning or network connection take up a smaller amount of the overall costs, while only the costs for modules, cables and other components increase.

4.2.2 OPEX PV plant

In general, solar power systems have no operation costs as no fuel is required to generate electricity, nevertheless, they do require regular maintenance. For this study, 1.5% of the investment costs represent the OPEX, given the assumption that maintenance work on rooftops might bear additional expenses like risk premiums for the maintenance workers.

4.2.3 Revenues

During regular days without match, the peak production of the PV plant sometimes exceeds the demand of the stadium. By selling this excess electricity to the grid, a feed-in tariff (FIT) is given for every kWh electricity fed into the grid. The FIT for PV plants >750 kWp in Germany has been determined by a tender system since 2017. Since then until 2019, the FIT tariff for utility-scale PV plants above 750 kWp has been 5.6 €ct/kWh in average, with maximum values up to 8.91 €ct/kWh. [29] The FIT for calculations carried out in this thesis are set at 8 €ct/kWh. The regulations for the FIT are very likely to change completely in the future and are hard to predict [32]. For this calculation, a constant FIT is assumed over the 20 years with no divergence considered. Table 4.4 shows the excess electricity produced in course of one year and the potential revenues from receiving the FIT.

Table 4.4: Calculation of the annual revenues of the PVDG system

Variable	**Value**
Annual electricity production PV	2 453 MWh
Electricity covering stadium load PV	846 MWh
Annual exported electricity PV	1 608 MWh
FIT 2018	80 €/MWh
Annual revenues from grid feed-in	128 640 €

4.2.4 Electricity bill

Table 4.5 shows the covered demand by the DG and the PV plant, respectively. It can be seen that the annual load covered by PV is lower than the

Table 4.5: Calculation of the annual electricity bill for the stadium with DG and PV

Variable	**Value**
Total annual load stadium	1 609 MWh
Annual load covered by PV	846 MWh
Annual load covered by DG	90 MWh
Annual remaining load covered by grid	673 MWh
Electricity price industry 2018[2][27]	197.7 €/MWh
Annual electricity from grid cost	133 052 €
Self-consumption surcharge from fossil fuels	60.5 €/MWh
Self-consumption surcharge from RE	27.5 €/MWh
Annual surcharge for self-consumption diesel	5 445 €/MWh
Annual surcharge for self-consumption PV	23 265 €/MWh
Annual total electricity bill	161 762 €

4.2.5 Emissions

As in the previous Chapter, the CO_2 tax is also applied for this system (see Table 4.6) with an annual increase of 10%.

Table 4.6: CO_2 tax for PVDG system

Variable	**Value**
total CO_2 emissions	30 tCO_2e/year
CO_2 emission tax	30 - 180 €/tCO_2e
tax increase per year	10%
total CO_2 tax costs 2018	900 €
total CO_2 tax costs 2037	5 504 €

4.2.6 Total CAPEX and OPEX PVDG system compared to DG system

The investment, operation and maintenance costs for both the rooftop PV plant and the DG is shown in Table 4.7, as well as the total CAPEX and OPEX.

Table 4.7: CAPEX and OPEX of the PVDG system

<table>
<tr><th>Variable</th><th>PVDG system</th><th>DG system</th></tr>
<tr><td>CAPEX PV</td><td>1 260 000 €</td><td>-</td></tr>
<tr><td>Annual OPEX PV</td><td>18 900 €</td><td>-</td></tr>
<tr><td>CAPEX DGs</td><td colspan="2">411 600 €</td></tr>
<tr><td>Annual fixed OPEX DG</td><td colspan="2">14 080€</td></tr>
<tr><td>Fuel costs 2037 (case 2)</td><td colspan="2">14 756€</td></tr>
<tr><td>Annual electricity bill</td><td>161 762 €</td><td>305 553 €</td></tr>
<tr><td>Of which self-consumption surcharge</td><td>28 710 €</td><td>5 445 €</td></tr>
<tr><td>Annual CO_2 tax</td><td colspan="2">900 - 5 504 €</td></tr>
<tr><td>Total CAPEX</td><td>1 671 600 €</td><td>411 600 €</td></tr>
<tr><td>Total OPEX 2037 (no CO_2 tax)</td><td>209 498 €</td><td>400 136 €</td></tr>
<tr><td>Total OPEX 2037 (with CO_2 tax)</td><td>214 898 €</td><td>405 536 €</td></tr>
</table>

The OPEX of the PVDG system are shown in Figure 4.5.

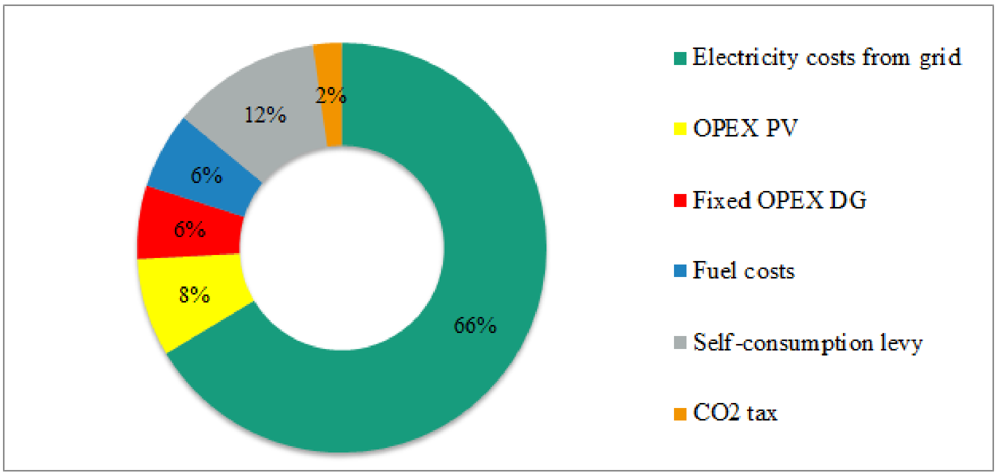

Figure 4.5: Breakdown of OPEX for the PVBES system (*own illustration and calculations*)

4.3 Results and conclusion

By feeding excess electricity into the grid, a FIT is received as reimbursement. The first NPC result is calculated with the FIT as the only revenue. Additional calculations are carried out by selling electricity on the spot market with Day-Ahead prices where selling during high price hours and purchasing electricity during low price hours is included in the strategy. This method is far from flawless, as the exact prices cannot be known in advance. This should be kept in mind when looking at the CFs that occur via the electricity market. Nevertheless, with the market premium the FIT is ensured to the electricity producer which is why a combination of FIT and spot market trading is considered as well. In Table 4.8 these results, as well as the difference given by applying a CO_2 tax and without the taxation are presented.

Table 4.8: NPC results without and with CO_2 tax on fixed tariffs, spot market trade and market premium

	FIT	Spot Market	Market premium
Annual revenues	128 640 €	69 914 €	81 445 €
Total OPEX 2037 (no CO2 tax)	251 857 €	126 720 €	126 720 €
Total OPEX 2037 (with CO2 tax)	257 361 €	132 224 €	132 224 €
Net CF 2037 (no CO2 tax)	- 96 448 €	- 42 256 €	- 28 325 €
Net CF 3037 (with CO2 tax)	- 101 950 €	- 47 760 €	-33 830 €
NPC without CO2 tax	3 459 440 €	2 471 759 €	2 217 858 €
NPC with CO2 tax	3 510 969 €	2 523 306 €	2 269 405 €

Between the NPC with fixed prices applied and the NPC of trading on the Day-Ahead market, a gap of almost 1 million € is given. One main reason for the fixed price NPC of the PVDG system being economically less favourable than spot market trading is the low FIT (80 €/MWh) compared to the electricity costs for industries (197.7 €/MWh). This is because PV plants with capacities greater than 750 kWp have to take part of a tendering process that will decide the FIT, and the FIT considered here is already the higher average compared to the historic FITs of between 56 €ct/MWh to 89 €ct/MWh [29]. Still, results from direct market trading should be viewed critically since, as mentioned before, Day-Ahead market prices can only be approximately predicted and the trade cannot always be carried out with optimal CFs. Still, the results give an idea of the advantages of trading on the energy market. It can also be seen that similar to the DG system, the proposed CO_2 tax has very little impact on the the overall NPC in course of the 20 years. Figure 4.6 shows all the results of the PVDG system compared to each other.

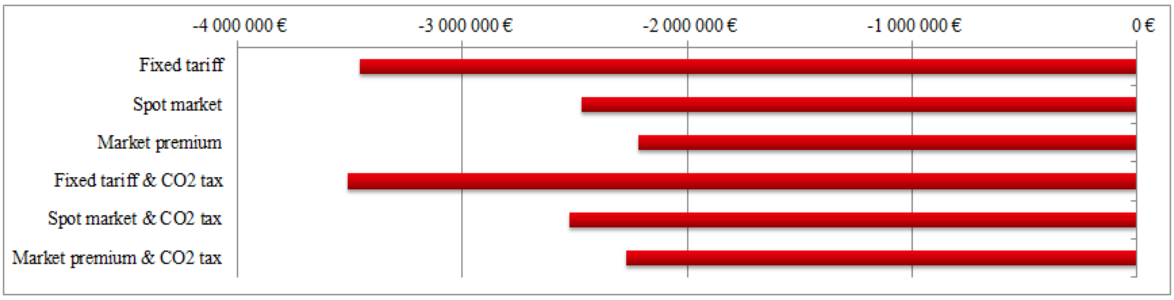

Figure 4.6: NPC results of the PVDG system including CO_2 tax (*own illustration and calculations*)

While the NPC is significantly lower than of the DG system, the annual net CF from the operation of the system remains negative as the expenses are higher than the revenues. Therefore the investment is never amortised. Furthermore, despite the PV plant and the resulting consumption of RE instead of the energy mix from the grid, the DG units still operate during the match and the emissions remain unchanged in both systems.

5 | Photovoltaic and Battery system

In order to propose a different, innovative solution to the DG based system that has no emissions during operation, a utility scale battery storage is proposed. In this Chapter a techno-economic feasibility study is carried out by taking the 1.8 MW rooftop PV plant in combination with a battery storage as electricity supply for the stadium. This chapter explains the system and technical characteristics in the first sections, followed by the input CAPEX and OPEX for the calculation of the system's NPC. Finally, different scenarios concerning capacity sizes and unit prices are calculated and compared.

5.1 System description

In this system, no fossil-fuel based units are used by the stadium owner to cover the electricity demand. When disregarding the energy mix from the grid, this system is emission-free during the operation-phase. For days with low solar irradiation mainly during winter months, the remaining electricity to charge the battery for the game is purchased from the grid. Figure 5.1 shows a graphical representation of the model.

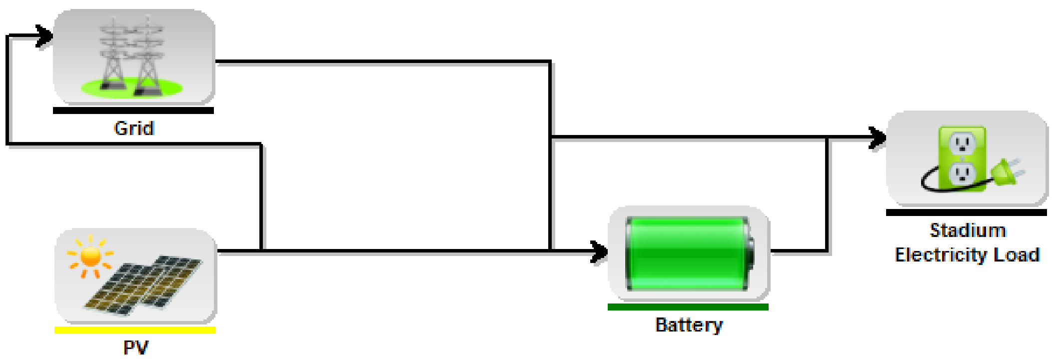

Figure 5.1: Graphical representation of the PVBES system (*own illustration from energyPRO*)

5.1.1 Battery storage technologies

There are different types of batteries in use to combine with PV plants, with Li-Ion and lead batteries being the most common ones. Lead-based batteries hold the highest share on the worldwide battery market, even though it is expected to decrease in the following years [23]. However, it is estimated that in 2014, around 94% of battery storage installed for PV in Germany were Li-Ion batteries and since the prices of Li-Ion batteries are constantly dropping, this trend is expected to continue [31]. Another emerging technology that is gaining more and more attention in Germany is Vanadium-Redox-Flow (VRF) [24], and in order to have a comparison to the two mostly used batteries, VRF is looked at more closely. The technical characteristics were researched in a life-cycle-assessment (LCA) study in [111] and complemented with data from [31]. The LCA was carried out with focus on recycling potential for all battery types and the results were characterised through ecological points, with higher ecological points representing a worse ecological impact. This research found that Li-Ion batteries have the lowest ecological impact with 0.01 points/kWh usable capacity (Low impact), compared to PbA batteries with 0.02 points/kWh (Medium impact) and

VRF batteries with 0.029 points/kWh (High impact).

Table 5.1 shows the battery characteristics for Li-Ion (data for Li-Ion batteries refer mainly to Lithium-Iron-phosphate and lithium-mangan-cobalt-oxide technologies), lead and VRF batteries. The prices take into account the size of the battery and the economy-of-scale, therefore they are somewhat below average prices of e.g. household-size batteries.

Table 5.1: Technical and other characteristics of different battery technologies [31, 59, 61, 62, 111–114]

Technology	**PbA**	**Li-Ion**	**VRF**
Lifetime	10 years	20 years	20 years
Life Cycles + remaining capacity	2 000-4 000 80%	4 000-10 000 80%	>10 000 NA
Specific energy	25-40 Wh/kg	100-150 Wh/kg	10-25 Wh/kg
Depth of Discharge	50-60 %	80-100 %	100 %
Efficiency	70-87 %	90-97 %	85 %
Ecological impact	Medium	Low	High
Average Price	150-300 €/kWh	375-1 200 €/kWh	900-1 200 €/kWh

As can be seen, the VRF battery is not far behind the other two more popular technologies. However, the current price and market of VRF in Germany hamper the choice for wider implementation [58]. For the stadium, three criteria apply as a requirement for the batteries:

- Cost: in order to achieve an economically favourable result, the battery costs have to be kept low
- Ecological impact: As this analysis aims to provide an environmentally friendlier solution than the use of DGs, the impact should not be too harmful
- Size: The designated area for the battery is restricted, therefore a high specific energy is required.

Given the low costs, but also the positive characteristics concerning environmental impact, high efficiency, specific energy and the high expected lifetime, the Li-Ion battery technology is chosen for further calculations, as it meets all of the above mentioned criteria.

5.1.2 Stadium supply from PV and the battery

The input values used in this thesis was provided by a German battery retail company. Following Table 5.2 lists the technical parameters of the battery considered.

Table 5.2: Input values of the battery storage

Variable	Value
Maximum capacity	4.018 MWh
Utilisation	95%
Depth of Discharge (DoD)	100%
Rated capacity	3.800 MWh
Charging power & efficiency	0.7 MW 97%
Discharging power & efficiency	0.7 MW 97%
Self-discharge [115]	5%/month
Net available capacity after 10 years	3 MWh

The decision to use a capacity of 4 MWh for the battery derives from the condition that the unit has to be able to supply the electricity load during a match for four hours. Even though this size results in high investment and maintenance costs, as it is explained in the later sections, the capacity serves as a good example for utility scale usage. Different capacities are explored in Section 5.3.1.

Note that due to operation management of the battery, the self-discharge rate and overall efficiency losses, the available capacity of the battery decreases continuously. When only 80% of the capacity is left, the BESS reaches the end-of-lifetime [115]. The decreasing capacity is not taken into account in the economic calculations in this thesis, thus setting a significant delimitation for the actual results which is discussed in Chapter 7.

5.1.3 Electricity production

The PVBES system's results for electricity production and other output values are shown in the following Table 5.3.

Table 5.3: Energy production and operation data calculated by energyPRO

Variable	Value
Annual electricity consumption stadium	1 608 MWh
Annual electricity production PV	2 453 MWh
Electricity covering stadium load from PV	884 MWh
Electricity from PV charging battery	1 088 MWh
Annual exported electricity from PV	481 MWh
Electricity covering stadium load from battery	726 MWh
of which electricity from PV plant	340 MWh
self-reliance of PVBES system	76%
Annual exported electricity from battery	1181 MWh
Annual imported electricity to charge battery	962 MWh
Annual electricity losses	142 MWh

With the PVBES system, the entire load of the stadium can be supplied through the battery, with only 258 MWh required to be purchased from the grid in addition to the PV plant's production. The production is graphically shown in Figure 5.2.

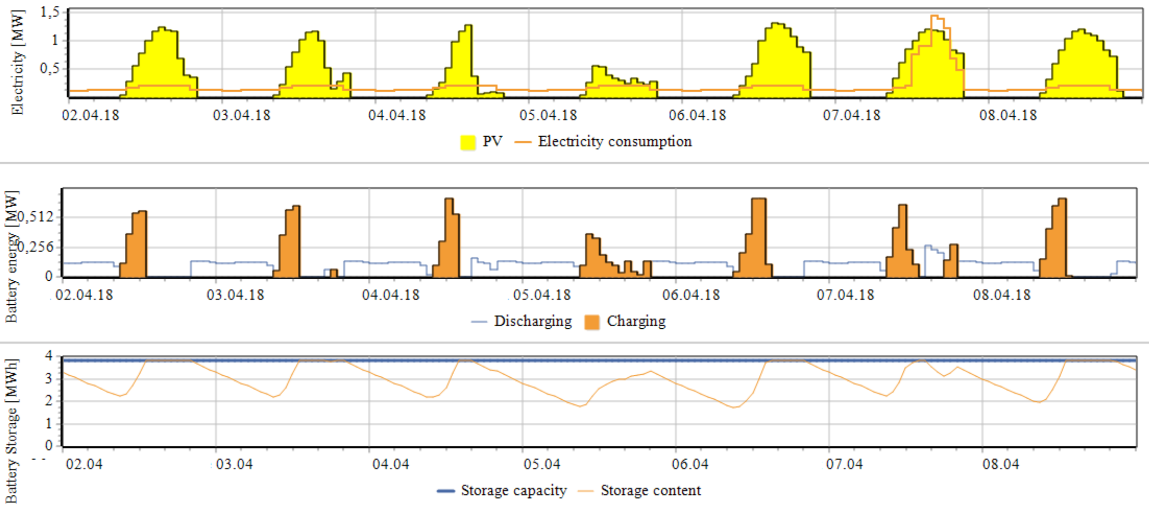

Figure 5.2: PVBES system with PV electricity production and stadium electricity consumption (top), charging and discharging of battery storage (middle) and the battery state of charge and capacity (bottom) (*own illustration from energyPRO*)

Even with the high peak consumption, a significant amount of the game can be supplied from the PV plant, whereas the rest is covered by the electricity stored in the battery. The energy flows are represented graphically in Figure 5.3.

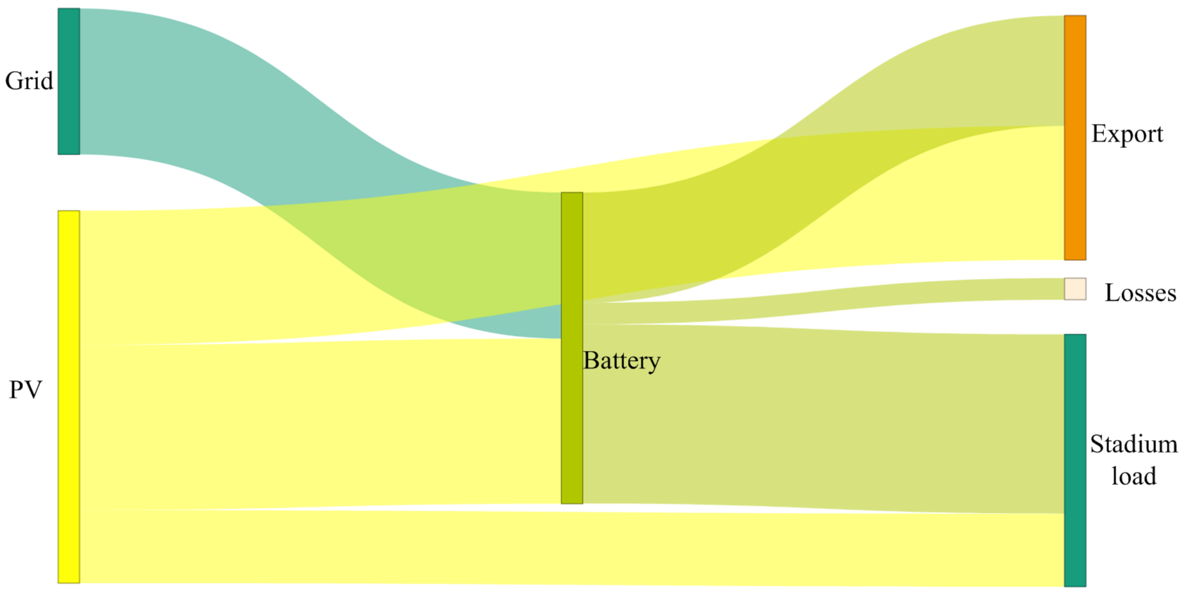

Figure 5.3: Sankey diagram of the energy flows covering the stadium load and being exported from the PVBES system (*own illustration with calculations from energyPRO*)

5.2 Economic assessment

The price for the battery is determined by a retailer who provided a price suggestion for a Li-Ion battery with the data listed in Table 5.2. This price was compared to and confirmed by potential prices for Li-Ion battery above 4 MWh found through literature research. The price indicated here includes also the power electronics and the control engineering according to the retailers who were contacted. As transportation costs are not taken into account in the previous systems, they are neglected here as well. The CAPEX and OPEX of the battery storage are shown in Table 5.4.

Table 5.4: CAPEX and OPEX of the 4 MWh battery storage

Variable	**Value**
CAPEX 4 MWh battery storage	1 500 000 €
Price per kWp	375 €/kWp
OPEX 4 MWh battery storage (annual)	30 000 €
OPEX: amount of investment cost	1.5%

5.2.1 CAPEX battery

The costs strongly vary especially for lithium based batteries, mainly between 400 and 1000 €/kWh, with a decreasing price for larger scale projects (>1 MW) [14]. Some retailers as well as [116] have indicated 625 €/kWh as an average price for Li-Ion batteries to combine with PV, however, the exact size of the project was not specified and reflected on in the price. One retailer has provided a specific price offer, which includes the two battery units that cover the required 4 MWh, as well as the inverter, transformer, cooling and control of the battery. Both the batteries and the power electronics are placed into two containers, which is a size that is appropriate for the available space intended for the project. With a total cost of 1 500 000 € offered by a retailer, the price per kWh would be 375 €. For the economic assessment, this price is used for further calculations.

5.2.2 OPEX battery

The OPEX is calculated by taking 2% of the investment costs, as determined in [95] and [96].

5.2.3 Revenues

During regular days without match, the peak production of the PV plant sometimes exceeds the demand of the stadium. By selling this excess electricity to the grid, a feed-in tariff (FIT) is given for every kWh electricity fed into the grid. The FIT for PV plants >750 kWp in Germany has been determined by a tender system since 2017. Since then until 2019, the FIT tariff for utility-scale PV plants above 750 kWp has been 5.6 €ct/kWh in average, with maximum values up to 8.91€ct/kWh. [29] The FIT for calculations carried out in this thesis are set at 8 €ct/kWh, with no degression considered over the duration of 20 years, given that FIT regulations are very likely to change completely in the future [32] with no suggestion about whether the changes will benefit the PVBES system or put it at a disadvantage. Table 4.4 shows the excess electricity produced in course of one year and the potential revenues from receiving the FIT.

Table 5.5: Annual revenues from the FIT calculated by energyPRO for the PVBES system

Variable	Value
Annual electricity production PV	2 453 MWh
Electricity covering stadium load	1609 MWh
Annual exported electricity PV	481 MWh
FIT 2018	80 €/MWh
Annual revenues from grid feed-in	38 480 €

Note that only electricity from the PV plant is reimbursed with the FIT. That is because electricity from the battery can be from both the PV plant or the grid, therefore the electricity cannot be viewed entirely as produced from renewable sources. As no other selling option is considered in the FIT scenario, electricity exported from the battery is not remunerated which results in a significant loss of potential income.

5.2.4 Electricity bill

Table 4.5 shows the covered demand by the DGs and the PV plant, respectively. For the self-consumption surcharge it is assumed that electricity consumed from the battery storage received the same reduction of the self-consumption surcharge as RE units do.

Table 5.6: Calculation of the annual electricity bill for the stadium with DGs and PV

Variable	Value
Annual total load covered	1 609 MWh
Electricity price industry 2018[1][27]	197.7 €/MWh
Annual imported electricity	962 MWh
Annual cost of purchased electricity	190 187 €
EEG surcharge	27.5 €/MWh
Annual surcharge for self-consumption	44 248 €/MWh
Annual electricity bill	234 345 €

5.2.5 Total CAPEX and OPEX

The total costs of all three systems are shown in Table 5.7 as a comparison.

Table 5.7: CAPEX and OPEX of the PVBES system compared to the PVDG system and DG system (including CO_2 tax) with fixed tariffs considered

Variable	PVBES system	PVDG system	DG system
CAPEX battery	1 500 000 €	-	-
Annual OPEX battery	30 000 €	-	-
CAPEX PV	1 260 000 €		-
Annual OPEX PV	18 900 €	18 900 €	-
CAPEX DG	-	441 600 €	
Total OPEX DG (2037)	-	24 064 €	
Annual electricity bill	190 187 €	161 762 €	305 553 €
of which self-consumption surcharge	44 248 €	28 710 €	5 445 €
Annual CO_2 tax	-	900 - 5 504 €	
Total CAPEX	2 760 000 €	1 671 600 €	441 600 €
Total OPEX (2037)	144 063 €	214 898 €	405 536 €

The OPEX of the PVBES system are shown in Figure 5.4.

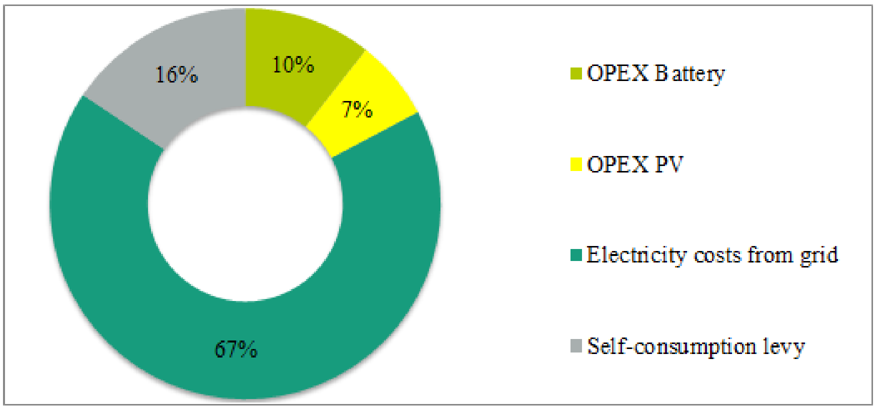

Figure 5.4: Breakdown of OPEX for the PVBES system (*own illustration and calculations*)

Similar to the DG system in Chapter 3 and the PVDG system in Chapter 4, the OPEX of the PVBES system is slightly dominated by the high costs of the electricity bill. This is because electricity needs to be imported from the grid to charge the battery (mainly before match) in order to supply the load that cannot be covered by the PV plant. Nevertheless, this also means that a potential reduction of the industry electricity price would have a considerable impact on the NPC of all systems that are assessed in this thesis.

5.3 Results and sensitivity analyses

First calculations of the NPC for the PVBES system are carried out by taking the average industry electricity prices of 2018 and the average FIT that was set for different utility scale PV plants through tendering schemes between 2017 and 2019. Table 5.8 shows the results of the calculations. The possibility of a higher FIT is considered as well, like in Chapter 4 with the PVDG system. Finally, the market premium scheme is calculated as the third relevant market trading option.

Table 5.8: Results of the NPC for the PVBES system on Fixed tariffs, spot market and the market premium calculated by energyPRO

Input data	Fixed tariffs	Spot market	Market premium
Annual revenues	38 480 €	139 275 €	149 023 €
Total OPEX (2018)	283 335 €	163 535 €	163 535 €
Annual net CF (2018)	- 244 855 €	- 24 260 €	- 14 512 €
NPC	8 151 463 €	3 294 181 €	3 079 540 €

A positive net CF in a year is achieved with neither of the three scenarios as the expenses remain greater than the revenues. The CFs of the market premium are shown in Figure 5.5.

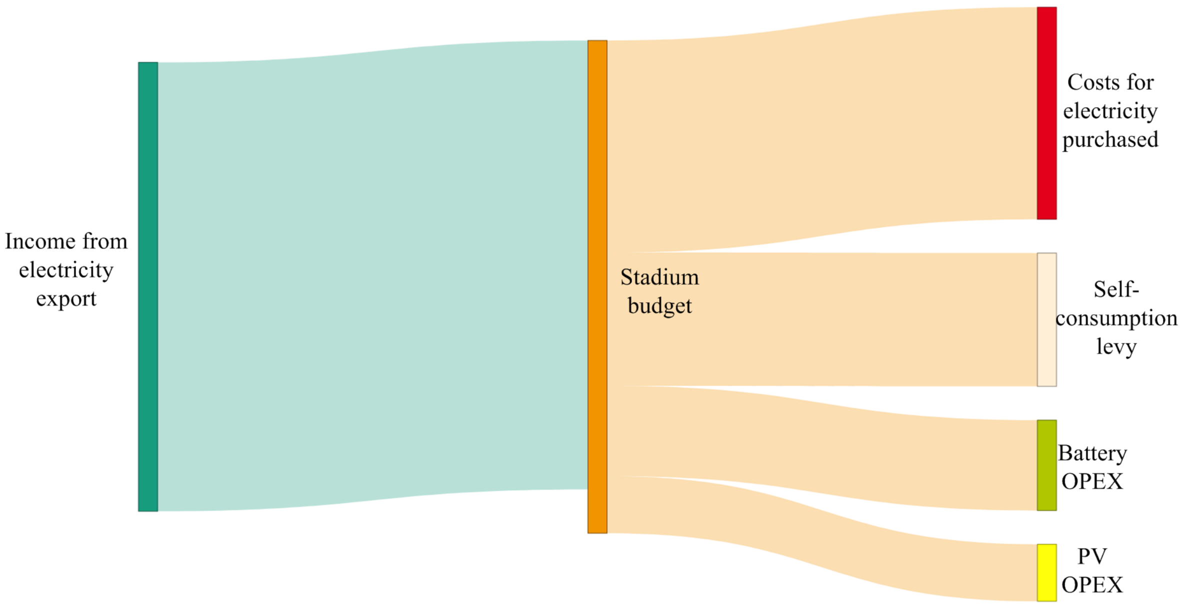

Figure 5.5

To compare the NPCs of all three systems, their results are shown in Figure 5.6.

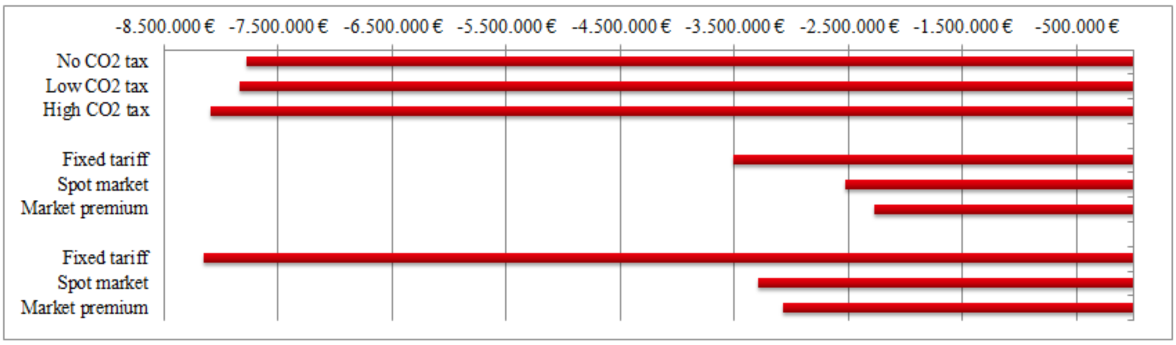

Figure 5.6: (NPC results of the DG system (top three), PVDG system including CO_2 taxes (middle three) and PVBES system (bottom three) calculated with energyPRO

Considering that the DG system's NPC after 20 years is greater than 7 million euros, the

PVBES system offers a better economic choice than the "traditional" DG system. It does however not surpass the economic advantage of the PVDG system which still uses DGs for powering the match, when the trading strategies are directly compared. In the following subsections, different input parameters are considered in order to look at their effect on the NPC of the PVBES system.

5.3.1 Battery capacity

Considering that the high CAPEX and OPEX for the Battery derive from the capacity of 4 MWh of the battery storage, calculations are carried out with two smaller capacities. Note that this does not align with the requirements given by the stadium operators as the battery storage would not be able to supply the demand for the whole stadium in case of a power outage. However, in order to show the difference of the NPC with other, smaller capacities, the calculations are carried out considering the same price or 375 €/kWh as taken for the 4 MWh battery storage. The capacities considered are

- 3 MWh
- 2 MWh

For the calculation, the economically most favourable strategy previously determined, namely receiving the market premium and applying spot market trade. The input and results can be seen in Table 5.9.

Table 5.9: CAPEX and OPEX of the battery storage with smaller capacities as well as annual OPEX and NPC results of the PVBES system calculated with energyPRO

Variable	3 MWh	2 MWh
CAPEX	1 125 000 €	750 000 €
OPEX	22 500 €	15 000 €
Total annual OPEX (2018)	145 811 €	128 545 €
net CF (2018)	- 10 388 €	- 6 293€
NPC	2 361 733 €	1 896 566€

It can be seen that a reduction of the battery capacity only offers minor advantages. Indeed, reducing the capacity to half-size even results in a higher NPC than with a 3 MWh battery capacity. This is because enough revenues can be made with the 3 MWh battery to cover the higher OPEX and CAPEX. However, both options already have a lower NPC after 20 years than the PVDG system.

5.3.2 Battery price

Given that the considered battery price is proposed by one retailer, there is a certain probability for prices varying if other retailers are contacted. Furthermore, as battery prices are constantly dropping, a lower price would be more likely in the future. Indeed, in a publication by the European Commission it is predicted that prices for stationary Li-Ion batteries will be as low as 150 €/kWh by 2030 [117]. Additionally, for considering an investment of the proposed kind in the future (2030), two hypothetical prices are considered for the calculation as well:

- 150 €/kWh, price prediction for Li-Ion batteries by 2030

- 200 €/kWh, price prediction for Li-Ion batteries between 2020-2030

The CAPEX and OPEX, and resulting net CF and NPC would therefore be as shown in Table 5.10. The income and expenses from the market premium is used for the calculations.

Table 5.10: CAPEX and OPEX of the battery storage, as well as annual OPEX and NPC results of the PVBES system calculated with energyPRO

Variable	150 €/kWh	200 €/kWh
CAPEX	600 000 €	800 000 €
OPEX	12 000 €	16 000 €
Total annual OPEX (2018)	145 535€	149 535 €
net CF (2018)	3 488 €	- 512 €
NPC	1 783 198 €	2 071 274 €

Naturally, the lower investment cost and, assuming that OPEX drop in the same pace as investment costs, the lower OPEX result in a fairly more favourable economic result, which makes the PVBES system economically more feasible than the PVDG system. It can therefore be argued that investments will pay off more likely within the next 5-10 years if Li-Ion battery prices continue to decrease as predicted.

5.3.3 Other PV plant capacities

In order to determine the impact the PV plant size has on the overall results, following different capacities for the PV plant are considered in addition to the 1.8 MW PV plant and included into the calculations:

- 1.4 MW
- 2.2 MW

Table 5.11 lists the electricity production, expenditures and the results with the two different PV plant capacities. Note that for the 1.4 MW system, the investment costs per kWh are higher than for the 2.2 MW plant in accordance with the economy-of-scale effect. Once again, for the NPC calculation, the combination strategy is applied.

Table 5.11: CAPEX and OPEX of the battery storage, as well as annual OPEX and NPC results of the PVBES system calculated with energyPRO

Variable	2.2 MW	1.4 MW
Annual electricity production PV	2 998 MWh	1 908 MWh
CAPEX	1 540 000 €	1 008 000 €
OPEX	23 100 €	15 120 €
Total annual OPEX (2018)	165 686 €	164 399 €
net CF (2018)	11 512 €	-42 399 €
NPC	2 786 517€	3 441 584 €

It can be seen that a smaller PV plant results in a higher NPC than the currently considered 1.8 MW, despite the lower CAPEX and OPEX. With the larger capacity of 2.2 MW, more electricity can be exported and therefore, higher revenues are achieved. However, given the production pattern of PV, the amount of electricity that has to be imported does not alter much. In addition, higher CAPEX and OPEX are paid, therefore a higher capacity does not present an economically more favourable scenario than the PVDG system, even though it does result in a lower NPC than with the 1.8 MW PV plant.

5.4 Conclusion

Comparing all the NPCs of the PVBES system, different scenarios occur through simple market trading of which some offer an economically more favourable scenario than the PVDG system. Nevertheless, by taking only spot market trading, even with addition of a market premium, under consideration, only some of the scenarios achieve a positive net CF during operation in a year, and none of the amortise the high CAPEX and OPEX of the system. The results are shown in Figure 5.7.

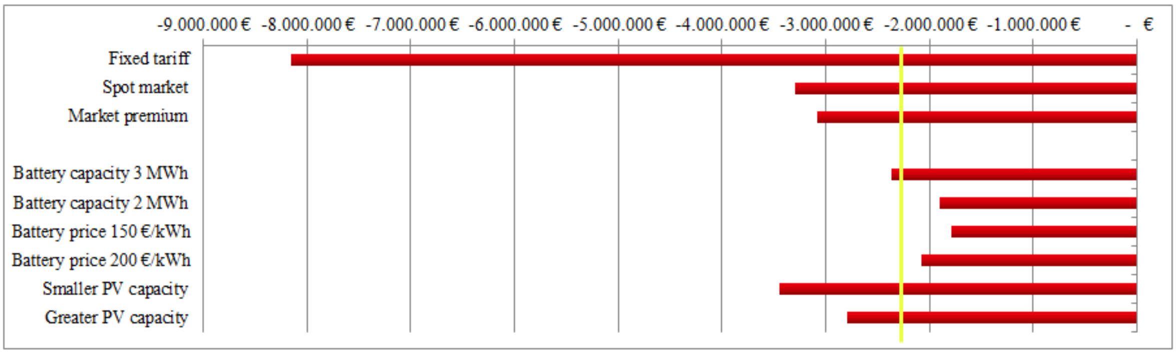

Figure 5.7: NPC results of the PVBES system with different scenarios considered, with the yellow line indicating the PVDG system's NPC in a market premium receiving scenario calculated with energyPRO

Judging from these results, the different PV capacities do not present an outcome with a smaller NPC than the PVDG system. As the NPC of the larger PV capacity is lower than that of the smaller capacities considered, it can be assumed that with twice the PV size a lower NPC could be achieved. However, given the restrictions of the rooftop area, this scenario would require to consider different areas around the stadium, for example by building shading construction for the parking area, in order to increase the possible PV plant capacity. Smaller battery capacities present better NPCs, with the 2 MWh battery resulting in an NPC lower than the PVDG system's. Even with a capacity of 3 MWh, an almost similar NPC is achieved. If the regulations for the electricity supply of match are altered or neglected, lower battery capacities would suffice for replacing the DG unit and thus save CO_2 emissions during operation, but also offer an economically more favourable option to the stadium operator. Finally, with lower battery prices considered, the PVBES system definitely offers the economically better option for the stadium operator. This means that within the following years until 2030, the option of using a utility-scale battery storage to replace fossil-fuel based backup units will become a feasible choice.

In order to not only offer a better choice than the DG or PVDG system but to amortise the high investment costs, other economic scenarios are considered in the following Chapter 6.

6 | Economic scenarios

This chapter assesses different trading options that can amortise the PVBES system's expenses. In the first Section, the profitability of buying and selling on the balancing market is discussed. The later Sections look into direct selling through PPAs by corresponding with different potential customers, namely a student residence located next to the stadium and the option of a park&ride facility and EV charging stations in the stadium's parking area.

6.1 Balancing Market

This direct selling of electricity has been disregarded for the profitability of battery storage until now given the feed-in regulations which made electricity trading on the German energy market economically unfavourable [33]. Indeed, as the results in the previous Chapter 5 show, the net CF from the operation when trading on the Day-Ahead market is still negative and therefore the option is not profitable, even though calculations are carried out where prices are known in advance and therefore the electricity selling and purchase is optimised.

In Germany, utility scale battery storage units are already used when trading electricity on the primary balancing energy market. Here, the battery operator reserves a specific amount of capacity and in case of grid instability due to too high or too low frequency, he charges or discharges the battery accordingly. For this available electricity the battery operator is remunerated by the TSO [33]. Figure 6.1 shows the average remuneration for the balancing trade in Germany between March 2018 and February 2019. Note that these prices consider 1 MW reserved per month.

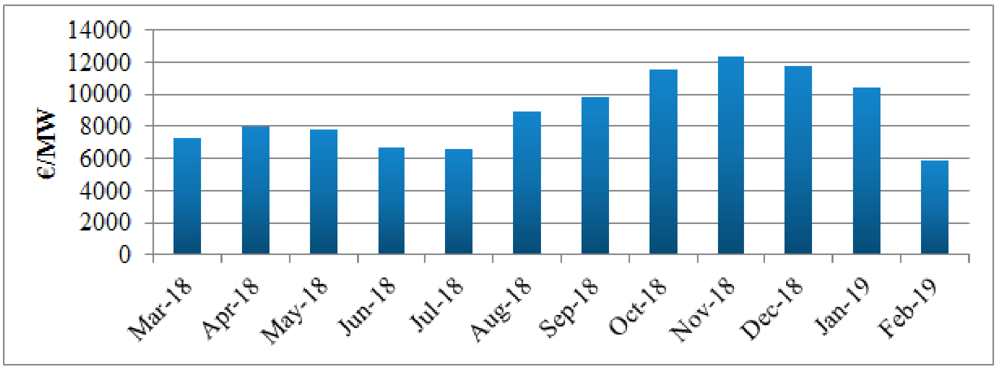

Figure 6.1: Historic average remuneration of the balancing load in Germany with 1 MW reserved load per month considered, March 2018 - February 2019 (*own illustration, data from [33]*)

For this calculation, no monthly changes are considered, but rather two scenarios with a higher and lower amount of remuneration for the balancing load in order to highlight the revenue potentials of this economic approach. The two scenarios are

- 12 395.2 €/MW/month as of November 2018 (Maximum)
- 5 956.1 €/MW/month as of February 2019 (Minimum)

In order to look at the economic feasibility of balancing market trade, for the weeks where no match takes place (34 weeks/year), 1 MW load is reserved every week. Considering that prices in Figure 6.1 are given for 1 MW primary balance load offered a month, the income is modified to match the potential load offered by the battery of the stadium. As 1 MW can only be offered in 34 weeks per year, or 7.8 months per year, it is assumed that for 7.8 months a year around 4 MW are reserved for the balancing market per month. That would result in the following income:

- 49 580.9 €/month
- 23 824.4 €/month

Table 6.1 shows the input parameters used for the calculations, as well as the results of the NPC. Note that the one time payment for the metering equipment is included for measuring grid frequency (price indications were found in [97]). This is done in order to avoid time losses through communication channels by enabling the operator to react as fast as possible in case of too high or too low frequency. Furthermore, the annual revenues from the export of remaining electricity is lower given the subtraction of the reserved load.

Table 6.1: Input and results calculated with energyPRO from the balancing market. The rest of the income is generated by applying the combined strategy from the previous Chapter 5

	Maximum	**Minimum**
Annual revenues from balancing market	386 731.8 €	185 830.6 €
Annual revenues from remaining exported electricity	138 475 €	
Costs to establish TSO connection	550 €	
Annual cost of purchased electricity	70 990 €	
Annual net CF (2018)	361 069 €	160 168 €
NPV	5 190 376 €	766 731 €
payback time	8 years	16 years

The results show that trading on the balancing market pays back the investment and operation costs with both high and low tariffs.

6.2 Student residence Freiburg

The revenue potential here is calculated by selling the excess electricity to a student accommodation located next to the stadium. For this facility, regular household prices are considered as indicated by a student dorm caretaker from another facility in Freiburg. As electricity is traded via the public grid, network charges for household consumers have to be included in the calculation. As of 2019, the network charge for households is 2.38 €ct/kWh [12]. Together with the EEG surcharge, the costs for direct selling to household consumers is 8.79 €ct/kWh. The annual consumption of the premises was around 7.8 GWh in 2018 as indicated by the caretaker. In this calculation the stadium operator enters into a PPA with the student residence which guarantees the purchase of the stadium's excess electricity for the following 20 years. In order to present a better offer than usual household electricity prices, the suggested price is set lower than the average household electricity price. Energy trading is also carried out on the spot market, so that required electricity can be bought at times of low electricity prices. The calculation input data as well as the results are shown in Table 6.2.

Table 6.2: Results from the PPA with a student residence calculated with energyPRO

Variable	**Value**
Annual exported electricity to student residence	2 668 MWh
Electricity price household	0.3 €/kWh
Suggested electricity price	0.28 €/kWh
Annual income	747 040 €
Costs of direct trade (EEG surcharge and household network charge)	88 €/MWh
Annual expenses of direct trading	234 784 €
Annual cost of purchased electricity	70 387 €
Net CF (2018)	348 721 €
NPV	4 918 489 €
Payback time	8 years

By directly trading excess electricity privately to the student residence, higher prices can be achieved than through direct trading on the electricity market. The CFs can be seen in Figure 6.2.

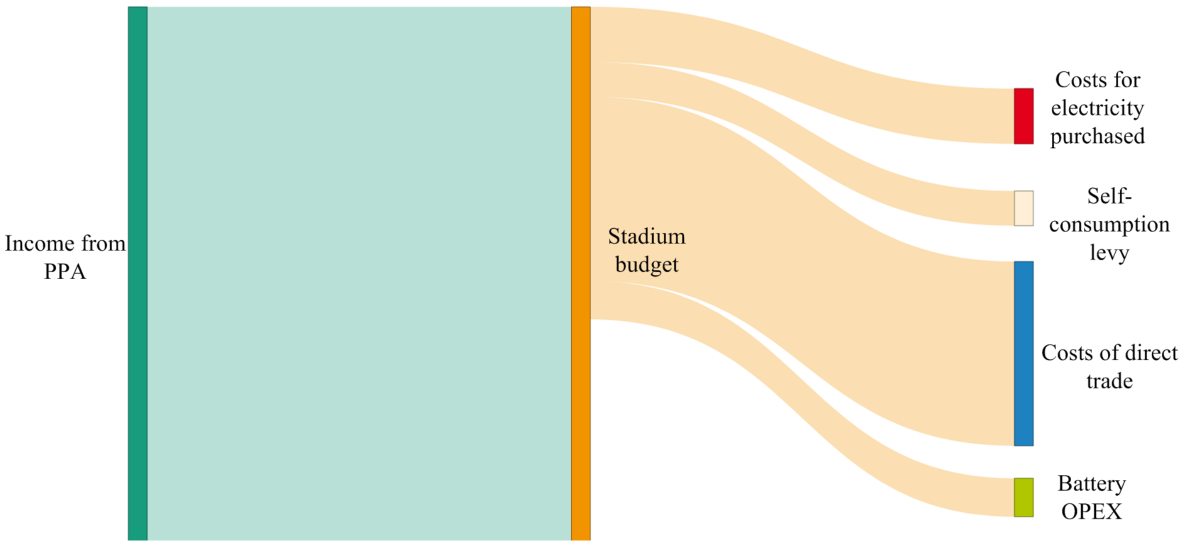

Figure 6.2: Sankey diagram of the CFs to and from PVBES system with the PPA student residence scenario considered (*own illustration with calculations from energyPRO*)

6.3 EV charging stations

The location of the stadium is close to the northern edge of the city. As it can be seen in Figure 6.3, there is no park&ride option offered by the city of Freiburg directly close to the stadium. In addition. there is a main street close to the stadium area which makes the location ideal for a park&ride facility.

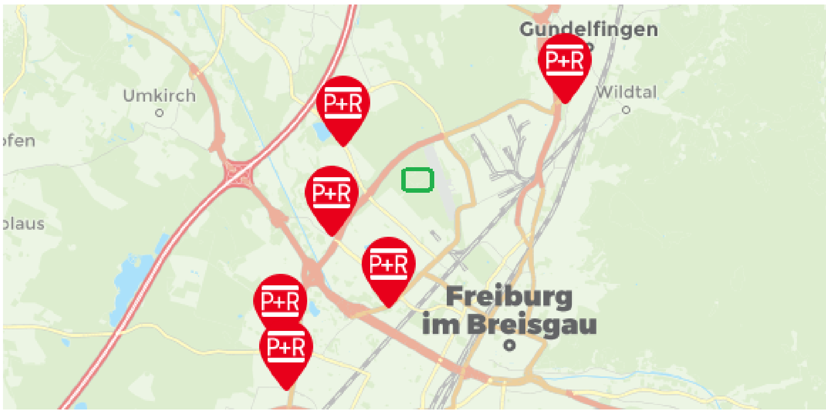

Figure 6.3: Park&ride options offered by the city in Freiburg and the location of the stadium (green) (*Modified illustration from [101]*)

With different public transportation possibilities (e.g. the tram is going to be extended with a station close the stadium), there is an option to use the parking area of the stadium as a park&ride facility outside match days. Furthermore, with the installation of charging stations in the parking area, additional revenues are created. In addition, the stadium operator has signed a PPA with the charging station operator that ensures the purchase of electricity from the stadium. As the demand for the charging stations is only 166.6 MWh per year (see Chapter 2), the rest of the excess electricity is traded on the electricity spot market in one scenario and sold to the student residence in another PPA scenario. Network charges are considered for EV charging (2.65 €ct/kWh in 2019 [12]) for the electricity sold to the charging station, which together with the EEG surcharge add up to 9.06 €ct/kWh. The financial input parameters to calculate the park&ride and EV charging scenario are given in Table 6.3.

Table 6.3: Input values of the EV scenario's NPC

Variable	Value
park&ride fee	0 €
Suggested electricity price	0.40 €/kWh
Annual electricity demand charging station	166.6 MWh
Annual income from EV charging	66 640 €

The results for both calculations can be seen in Table 6.4. The network charge and EEG surcharge is adjusted for the electricity sold directly to the student residence.

Table 6.4: Input values and results calculated with energyPRO of the EV scenario's NPC

	EV only PPA	EV + student PPA
Costs of direct trade EV (EEG surcharge and EV network charge)	90 €/MWh	
Costs of direct trade student residence	-	88 €/MWh
Annual expenses of direct selling	14 994 €	236 877 €
Annual income from export of remaining electricity	134 242 €	840 234 €
nnual cost of purchased electricity	74 183 €	
Net CF (2018)	18 557 €	368 424 €
NPV	- 2 351 393 €	5 352 330 €
payback time	-	8 years

The PPA with the EV charging stations does not create enough revenues to result in a positive NPV after 20 years. The revenues are high enough only when selling the remaining electricity to the student dorm. Given this result, the option of creating a park&ride facility out of the parking area alone would not be economically beneficial to the stadium operator. Figure 6.4 shows the CFs from the PPA combination scenario.

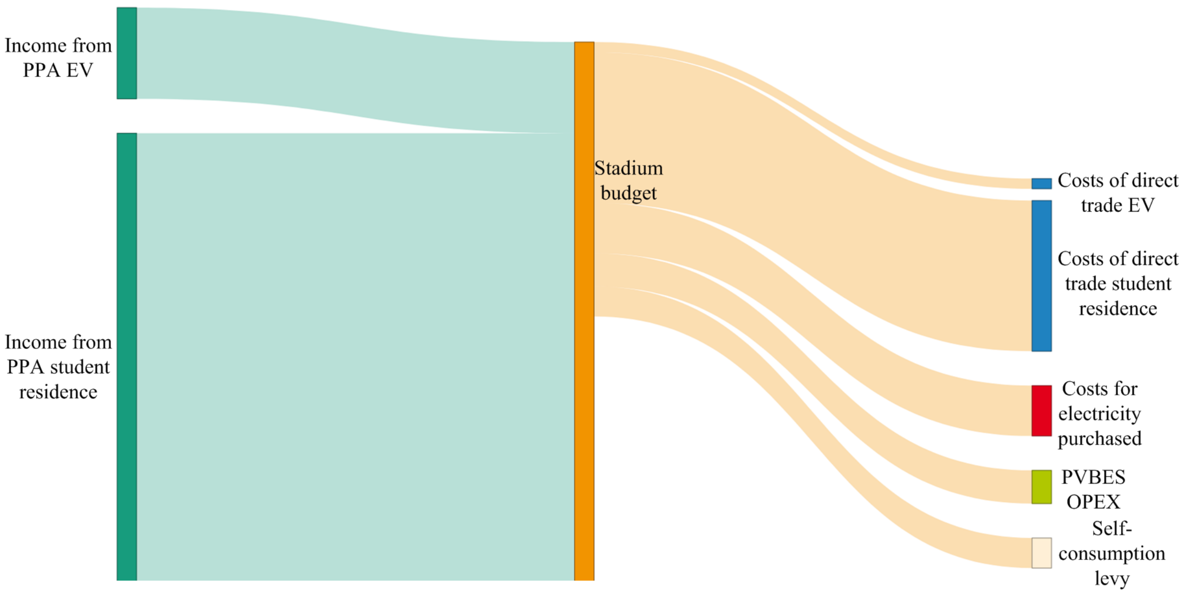

Figure 6.4: Sankey diagram of the CFs to and from PVBES system with the combined PPA scenario considered (*own illustration with calculations from energyPRO*)

6.4 Results and and break-even values

Figure 6.5 shows the results from this chapter's calculations. All three scenarios result in a positive NPV with a payback time of between 7 and 15 years.

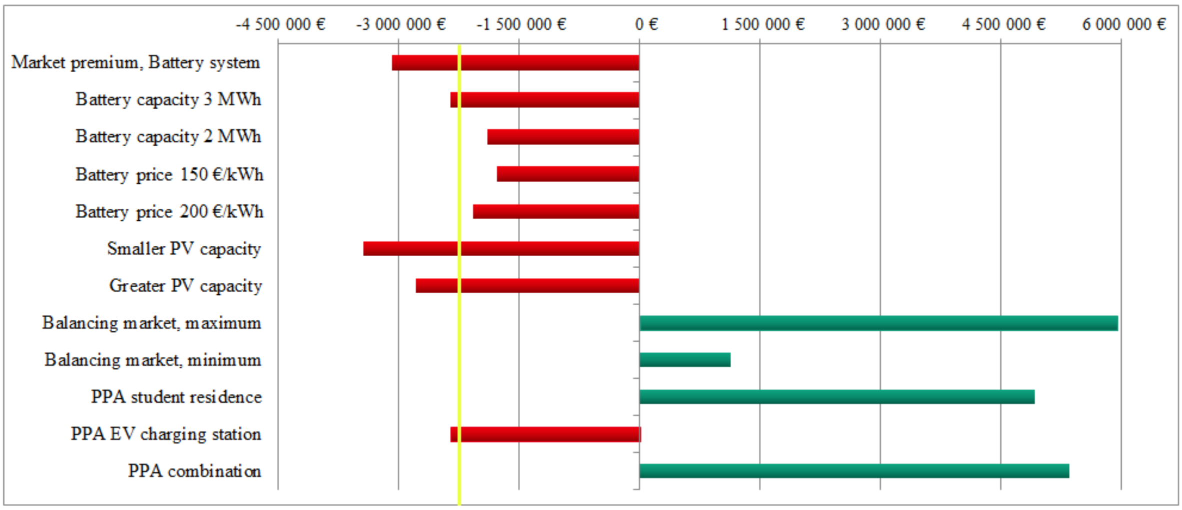

Figure 6.5: NPV of all economic scenarios of the PVBES system calculated with energyPRO compared to the NPC of the PVDG system with market premium scenario indicated by the yellow line

The largest potential for gaining revenues and amortising the investment and operation costs for the PVBES system lies in balancing market trade and PPAs with household-price paying consumers. However, for a time-span of 20 years, there is a high risk when relying on balancing market revenues as the main means to regain the expenses given that price developments are uncertain, as discussed in the next Chapter 7. Thus it can be concluded that the PPA presents the most promising economic scenario for the PVBES system.

6.4.1 Break-even of income

In this section the required minimum income for the PVBES system is identified in order to pay back the high investment and operation costs. With a trial-and-error approach the required income is determined with expenses that arise in the market premium scenario for the PVBES system. Table 6.5 shows the CFs including the required income to result in a positive NPV in the year 20.

Table 6.5: Input values of the market premium scenario with required income and results calculated with energyPRO to achieve a positive NPV after 20 years

Variable	Value
Annual cost of purchased electricity	70 367 €
OPEX PV and battery	48 900 €
Self-consumption surcharge	44 248 €
Total OPEX	163 535 €
Required annual income	290 000 €
net CF	126 465 €
NPV after 20 years	24 633 €
Payback time	20 years

It can be concluded that in order to amortise the expenses of the PVBES system, an annual income of approximately 290 000 € is required. As for all other calculations it should be kept in mind that the expenses do not take unforeseen expenses like required replacement of components before the end of lifetime into account. Thus the break-even income defined here does not include a risk-adjusted surplus.

6.4.2 Break-even of CO_2 tax

With direct comparison of the NPC results from fixed tariffs, Day-Ahead trading and the combination of those, the PVDG system is more favourable given the lower NPC after 20 years. Given that the proposed CO_2 tax from [5] is considered too low compared to the other OPEX of the PVDG system, a new tax is determined by calculating the difference of the NPC between the PV and PVBES systems and applying the difference as CO_2 tax. For comparison, the tax per CO_2 required to make the PVDG system with fossil fuel units economically less feasible is shown in Figure 6.6.

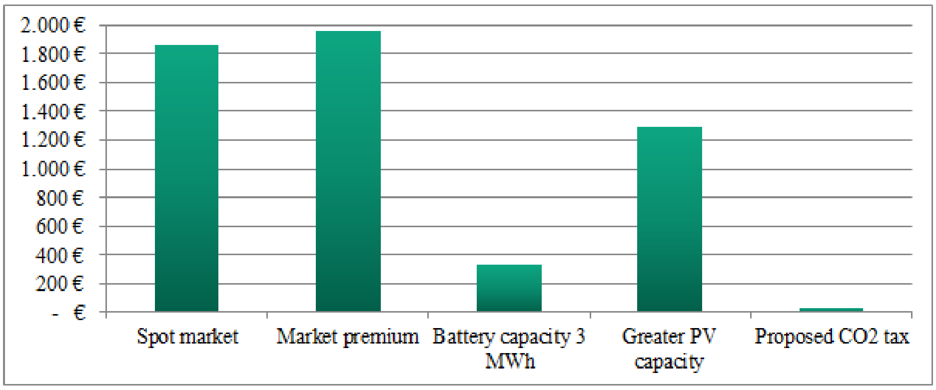

Figure 6.6: Identified required CO_2 tax for equal economic feasibility of the PVDG system and the PVBES system (*own illustration and calculations*)

It can be concluded that a much higher CO_2 tax is to be introduced if fossil fuel based units are to be put at disadvantage. However, it should be kept in mind that CO_2 taxes proposed here are constant and do not grow in course of the 20 years as they do in calculations of the DG system and PVDG system.

6.5 Conclusion

To sum up this chapter's results, the economic feasibility of the PVBES system can be achieved in optimal conditions, meaning that no unexpected costs like component replacement are required. A high potential lies in balancing market trading which is already a common market strategy used for battery storage systems in Germany, however, it has an unreliability which is discussed in Chapter 7. In addition, various PPAs can also improve the economic feasibility but have lower reliability as the contracts are mostly set for a duration of between 10 and 15 years. Still, the results show the potential that utility-scale battery storage systems have presently. With decreasing investment costs, this feasibility is expected to improve and be even more profitable in the future.

7 | Discussion

This chapter aims to look at the results found in this thesis from different aspects, as well as to mention potential research that could be added to this thesis in order to determine the feasibility of the proposed system. Based on these insights, a possible future outlook is considered a the later section.

7.1 Barriers and opportunities

During the identification of different costs and calculation of the NPC and NPV of the different systems, various elements were identified that could hamper, or support the implementation of the proposed PVBES system. These factors are briefly discussed in the following subsections.

7.1.1 Investment costs

The common perception about high investment costs for both utility-scale PV plants and BESS could be viewed as the main barrier that impedes the PVBES system solution from becoming more popular. That is because CAPEX data is often based on older information, whereas the prices for both PV and batteries (especially Li-Ion) are constantly dropping. This aligns with the findings of [17] and [18], as both conclude that PV is often discredited for large-scale implementation due to its high investment costs, even though it has been determined that electricity produced by PV is among the sources with the lowest LCOE [16].

7.1.2 EEG surcharge

A financial barrier that was identified in course of the calculations is the EEG surcharge that is to be paid for every kWh electricity consumed, even the electricity that is produced and consumed by the same user. This self-consumption surcharge accounts for 16 % of the expenses and therefore affect the net CF remaining from the operation, even though the surcharge is reduced around 40% when applied for self-consumption charges for electricity produced by RE sources [29]. It is debatable whether the 40% reduction will be granted in the future for the PVBES system proposed in this thesis, given that the battery is charged from both the PV plant and the grid.

With the constant growth of the EEG surcharge in the past years, electricity prices have been increasing as well despite the sinking spot market prices in Germany since the liberalisation of the energy market. The electricity price level has encouraged many private and also industrial consumers to invest in the self-reliance of their household or business. In order to reach the goal of covering 65% of the net electricity consumption in Germany by RE by 2030, the EEG surcharge is likely to remain stable or even increase further [8]. However, the consequences of increasing self-reliance for both the electricity market and the financial budget of the EEG is questionable; despite the surcharge being set for every kWh electricity consumed, the net income is likely to decrease which might result in a resuming growth of the EEG surcharge and therefore electricity prices. This, in turn, could result in even more consumers aiming for self-reliance and thus continue the vicious cycle.

On the other hand, different sources expect the EEG surcharge and therefore electricity prices in Germany to decrease in the following years [118, 119] given that many RE power plants are reaching the phase-out time of 20 years by 2020 and will therefore not be eligible to receive a FIT. Furthermore, a CO_2 tax that is discussed today could be included into the EEG budget and thus relieve consumers for paying a high EEG surcharge. Yet, it is unclear whether these two factors will affect the EEG budget significantly enough to result in a considerable drop of the surcharge. It is more likely that the surcharge will stabilise as expected by [8] in order to be able to support the installation and operation of new RE plants.

Finally, it should be considered how heavy the impact of the EEG surcharge could potentially be on the proposed PVBES system in the future. The surcharge is considered for every kWh consumed or traded and therefore has substantial impact of the CFs of the PVBES system by making up 16% of the annual OPEX, as it can be seen in Figure 5.4 in Chapter 5.1. Furthermore, the cost of direct trade that is applied for the PPAs includes the EEG surcharge and makes up around 59% of the total outgoing CFs. A possible growth of the EEG surcharge would thus significantly affect the NPV and therefore the economic feasibility of the PVBES system.

7.1.3 Balancing market

Even though trading on the balancing market offers a favourable solution by making profit after a payback time of between 7 and 15 years, there are risks in the uncertainty of balancing market prices for the future. With the introduction of more storage units that are used for stabilising the grid, the amount for remuneration might stabilise or even decrease in the future. On the other hand, a positive outlook can be expected concerning the demand for utility-scale battery storage units as more and more conventionally powered units are leaving the balancing market [33]. Nevertheless, despite the high profitability of electricity trading on the balancing market, the uncertainty should be kept in mind when considering the PVBES system.

7.1.4 Power Purchase Agreements

The PPA proved to be of substantial value for achieving the profitability of the PVBES system. By entering into a PPA, a fixed income can be set for the time of the agreement which can be up to 20 years. However, it should be kept in mind that electricity prices can likely change within that time and other, perhaps more profitable possibilities might remain unexploited given the fixed PPA. Therefore, considering a shorter time horizon for the PPA does not only bear risks but also potential for new opportunities.

On the other hand, with the phase-out of the EEG remuneration for RE plants that have operated for longer than 20 years, more and more providers are looking to alternative revenue options like PPAs. With the growing trend of these agreements and consequently more competitors, the offered price might have to be set lower than the suggested 0.28 €ct/kWh which would affect the end-result of the PVBES system. Still, with PPAs becoming more popular the potential of finding customers grows once the advantages for both the producer and the consumer become more clear. Therefore, it is one of the most promising scenarios identified for the PVBES system.

7.2 Reflection on methodology and results

This case study has the focus on a specific location with a facility that has an annual electricity load which is non-transferable to industries or utilities from other sectors. The chosen technologies to compare are also limited to one type of electricity production and one storage method. The results and delimitations of these choices are discussed in the following subsections.

7.2.1 Theoretical Framework

The theoretical framework provided a context from which the techno-economic feasibility of the proposed system could be assessed and also justified the need for the techno-economic analysis. Results from different research as well as the lack of in-depth research in the context of Germany points to an unawareness of the economic potential of battery storage systems. This lead to the application of the choice awareness theory which suggests four steps for raising choice awareness, namely by offering a technical alternative, conducting a feasibility study, identifying the relevant public regulations and making use of the democratic infrastructure to put the alternative into practice (see Figure 2.1 in Chapter 2). It can be argued that qualitative research could provide better insight into the awareness or lack of awareness of decision makers, and also the specific aims of for example stadium operators to for example maintain a sustainable image. However, given the agreeable results of the thesis and the comparatively uncommon practice of utility-scale BESS implementation, it can be argued that this is due to the lack of awareness of the economic potentials.

While the first two steps of raising choice awareness, namely considering a technical alternative and conducting a feasibility study are carried out in this thesis, a broader feasibility study can support the next two steps that address the public regulation and finally the democratic infrastructure of the area where the radical technological change is to be implemented . By widening the focus further from the techno-economic feasibility, more aspects like the socio-economic impact, the institutional changes and the policies related can be assessed more closely.

The theoretical framework elaborates on the choice of a case study to carry out the feasibility study as the generalisability of the case from a broader view can be limited when looking at a specific case. This is discussed later in this chapter. Given the varying opinions about case studies and the question about the scientific credibility mentioned by [78], one might argue that the unique load profile of the stadium makes it difficult to apply the findings of the study in a broader perspective. Therefore, certain parameters should be identified through the case study that can be applied in other contexts [77]. The parameters applicable and notable from this thesis are mainly the findings for the utility-scale PV plant and BESS. This is because prices considered are verified by most recent price indications as well as retailers in the German area. On the other hand, the unique situation of the stadium's match load to be powered fully by a back-up unit is highly unlikely to be applied elsewhere, therefore the comparison of the PVBES system to the DG system is one that is limited to stadiums in Germany. Nevertheless, with the expectation of the PVBES system to be economically not feasible, this case study contributes as a "theory-breaking rock" described by [79], since it contradicts the common perception of PVBES systems to be unprofitable.

The feasibility study was determined to be carried out from the point-of-view of the stadium operator, who is assumed to be the operator of all equipment in all three system scenarios. An additional calculation scenario that can be useful to compare to the results in the thesis would be an assessment of the economic feasibility for both the stadium owner and a new entity, the utility company. The respective ownership model is briefly mentioned in Chapter 2 (see Figure 2.4) but is neglected as it would exceed the scope of this thesis.

7.2.2 Energy saving measures

The calculations are based on a preliminary study from [71] where the electricity demand of the new stadium was identified. It is assumed that significant parts of the load consist of illumination, transmission of the event, and cooling in summer. With more extensive research, the exact load units could be identified and different energy saving measures could be implemented, for example by replacing loads with more energy efficient units, improving heating and cooling by turning down equipment for rooms or areas not in use, to name a few [120]. In this thesis, no energy saving measures are considered, which could be seen as a delimitation when considering the sustainability of stadiums. Nevertheless, given the focus of the analysis set with the research questions, energy saving measures are not part of the scope of this analysis.

7.2.3 Environmental assessment

For the environmental assessment, only the operational emissions from the DGs were considered. However, the manufacturing and transportation efforts, as well as the disposal of used units were not taken into account. A full LCA of all units would provide a better understanding of the impact that alternative technologies could have when replacing current ones. This is already taken into account in the course of choosing the type of battery storage as the ecological impact is one of the key factors, apart from the size and the cost of the battery. The choice is based on an LCA carried out by [111], where the recycling potential of the three battery types are included as well. The research concludes that Li-Ion batteries have the lowest impact compared to PbA batteries with medium, and VRF batteries with high ecological impact. For additional information, an LCA of rooftop PV plants and DG units could be considered.

7.2.4 Choice of electricity production

The electricity demand and production was separated from the heat demand and they were not assessed together, so combined heat and power production options were not considered. Nevertheless, the heat demand of the stadium is to be supplied through district heating and no fossil fuel units are used to cover the heat demand.

Since a solution with less emissions during operation is aimed for when compared to the DG system, various other options could have been explored. For example, the feasibility of wind power or combining wind and solar power might have been a possible alternative. However, with the use of a battery storage, the addition of wind power might have only led to unnecessary higher expenses while providing the redundant advantage of balancing out the residual load resulting from the PV plant's electricity production. By considering a scenario where electricity from the grid is supplied from 100% RE, a smaller PV plant or even no RE unit could be considered since a battery-only system would still provide the security of supply and have no CO_2 emissions during operation. However, given the economic advantages of producing electricity from a self owned PV plant, it is unlikely that any operator would choose a battery-only scenario.

Future of PV

Prices for PV have been constantly decreasing globally and it is debatable how long this price degression will continue. The economic feasibility for the PVBES system mentioned here therefore has more potential to become favourable with the sinking prices for Li-Ion batteries as the results in Chapter 5 show.

The positive results of both the PVDG system and the PVBES system raise the question whether PV will be considered as more significant in future projections or if it will continue to be slightly neglected as research mentioned in Chapter 1 points out. One of the main disadvantages of PV, namely the uncontrollable production times which do not follow the electricity demand curve and the resulting residual load that remains, could be solved by combining them with battery storage systems. Yet it seems that the main conception about PV and PVBES systems is that these systems are not economically feasible for plant operators. The constantly sinking costs of batteries combined with choice awareness raising through more research and distribution of the knowledge can potentially improve the common "image" of these systems and foster their further implementation.

7.2.5 Choice of storage

For this thesis, a battery storage is was considered and only different types of battery storage were looked at.Ddue to time restrictions it was decided to only look at the two mostly used technologies and look at one alternative technology that has potential to grow on the market in the future. Still, for a more thorough assessment, other battery types like nickel-cadmium or lithium-iron-phosphate could be included and considered. As discussed in Chapter 5, PbA and VRF BESS could potentially offer an alternative to Li-Ion batteries. Yet it has been determined that neither PbA nor VRF batteries fulfil the economic, ecological and space requirements.

One further option would be to look at other storage technologies, their technical and economic feasibility for the case and also environmental benefits or drawbacks. For example, pumped hydro storage is an option for storing excess electricity, and given the mountainous area close to the stadium, it could likely be implemented. No emissions derive from this system, however, these storage systems significantly alter the environment given the large area requirements [121]. Another option to consider would be hydrogen based storage systems, which is a promising storage technology regarding the energy transition towards RE, but the techno-economic feasibility still requires improvement before it can be implemented on a commercial scale [122]. EVs could also be considered as interim electricity storage, but the required scheduling to make the load available calls for new business schemes in order to make the solution feasible [123]. These are just a few alternatives to BESS, nevertheless, the unreliability as well as the previously mentioned requirements would likely not be fulfilled by these alternatives.

Battery lifetime

The management of charging cycles of the battery has a strong impact on the performance and the lifetime of the battery, which is why they should be considered when planning the use of the battery for different economic strategies. In this thesis, this aspect is neglected and it is assumed that the battery suffers no grave troubles that cannot be avoided through regular maintenance. This is an optimal scenario and it should be kept in mind that unexpected additional costs for the battery could arise in the course of the next 20 years of planning horizon. Furthermore, the capacity losses after a given time are not taken into consideration even though the end-of-lifetime of the battery is likely to be reached after 10 years. This delimitation could be avoided by for example considering investing into a new BESS after 10 years or by adding additional battery racks to increase the capacity.

7.2.6 Economic assessment

One limit of the economic assessment is the fact that only techno-economic factors were taken into account. An interesting aspect could be explored in a socio-economic assessment for example to identify the number of jobs provided given the maintenance works, operation for market trading but also the health benefits when DGs are replaced with battery storage systems as back-ups. Furthermore, these factors could be expanded for example on regional or even national scales by calculating the consequences of replacing the DGs of every stadium in Germany with utility-scale batteries.

Neglecting transport costs

Transport costs of the purchased production units were neglected for all three systems. This is because they can strongly vary depending on the retailer's location and price offer, as it is sometimes included in the overall expenses. Furthermore, it would narrow down the generalisability of the calculations even more to this one case. Since the three systems are compared to each other, the neglecting of transport costs may be overlooked, however, especially for the PVBES system some additional 8 000 € can be expected for transport costs of the battery storage according to a retailer. For the PV plant, around 1-1.7% of the total CAPEX may account for additional expenses for the transport and logistics as specified by another retailer, which in case of the 1.8 MW PV plant would be around 21 000 € in addition. The higher transport costs compared to the battery could be explained by the fact that the batteries can be transported with their containers while modules require the extra work of packing and unpacking them for transportation. Nevertheless, these expenses were not taken into account in this economic assessment and should be identified if further calculations are to be carried out.

CO_2 tax

There is no CO_2 tax in place in Germany as of 2019, even though discussions are ongoing given that CO_2 certificates are not resulting in reduced emissions as it was aimed for by the introduction of this scheme [5]. However, it is determined in this thesis that the proposed tax of 30 €/tCO_2e does not significantly affect the total expenses of the DG system and the PV system. Nonetheless it should be kept in mind that fossil fuel based units in this system are only used for around 5.6% of the total stadium load and therefore the conclusion of the effectiveness of the CO_2 tax cannot be viewed as a general conclusion. On the other hand, with the developments of the EEG surcharge and the consideration to use the CO_2 tax income to support the EEG budget, it is likely that the tax will be set higher than the current proposition.

FIT and market premium

For the FIT, an average price from historic data is taken by considering the tariff set through tendering schemes that are required since 2017 for PV plants with capacities greater than 750 kW. However, the FIT but also other remuneration schemes like the market premium are expected to change during the 20 years considered in this study [8]. Another critical aspect is the remuneration of electricity that is sold from the battery storage and not directly from the PV plant. As the electricity might be partly from grid charging and not from the PV plant, it cannot be guaranteed that a market premium is provided for all electricity sold by the PVBES system.

Electricity price

For electricity prices the average data is taken for both household and non-household tariffs. Considering that different electricity providers offer different tariffs, the prices calculated with in this thesis might not represent actual prices paid by the consumers. Nevertheless, an average is considered for all electricity prices considered in this assessment, therefore the uncertainty can be neglected.

Interest rate

As previously mentioned in Chapter 2, interest rates for investments in Germany have been decreasing over the past years [18, 87]. However, considering that the battery storage makes a significant part of the investment for the PVBES system and given that interest rates for utility scale storage are higher in other research [85, 88] than the one set in this thesis (2%), one can discuss the applicability of the interest rate given the different types of investments that are compared in this thesis. Nevertheless, since the inflation rate (1% in this thesis) is regarded separately, the real interest rate would be 3%. Still, by setting a rather low interest rate the profitability of all systems is favoured and no risks or future developments for either of the units are considered. This can be viewed as a strong limit to the reliability of the results.

7.2.7 Consequences of large-scale battery implementation

With storage systems, the option is given to trade electricity according to the market's high and low prices. It is debatable how an increased number of storage systems and operators taking advantage of this option will influence electricity prices in the future. With balanced loads through storage systems, the variation of the electricity price might balance out as well and therefore decrease the advantage of storage systems. Furthermore, as pointed out earlier, with the combination of RE and battery storage in both residential and commercial use, the self-reliance of those can be increased which brings up the question how increased self-reliance will influence the market and the CFs between operators, consumers and also the authorities.

7.3 Generalisability of the assessment

The topic of this assessment's applicability in broader levels is already briefly mentioned in Section 7.2.1. Some perspectives speak for, but most against the generalisation of this research on a broader perspective.

- Electricity prices considered in this thesis, as well as spot market prices, fuel price, FIT, remuneration on the balancing market and surcharges are real prices taken from Germany. The study can thus be broadened to a national level, but is limited to Germany given the chosen input values.
- The proposed CO_2 tax is limited to the German context as well, given that it derives from a proposal set for Germany, which again limits the case to the country.
- The case of the stadium, especially the regulations of the off-grid measure during game-events, is a national regulation and can, like the previous two factors, be broadened to all Germany but not further.
- Given the unique load profile of the stadium, exact results are limited to this kind of utility and cannot be compared to other utilities. However, the study can encourage the assessment of more case studies related to PVBES systems or BESS combined with RE in order to further demonstrate the economic potential of those.
- The effects of battery operation on its lifetime is not considered in this study. This leaves room for generalisation given that the operation strategy depends strongly on the supplied load profile and also market conditions. Nevertheless it should be kept in mind that this limitation also neglects monetary losses that occur through decreasing battery capacity or possible need for replacement of equipment within the time-horizon of 20 years.
- Transportation costs were neglected for all systems considered. These expenses can depend highly on the location of the system, which is why the considered area can be broadened from the current location.

It can be concluded that while the case itself can be applied in the context of Germany, it is limited to Germany only. Within that frame, the case narrows down to utilities with unusual load profiles, where the PVBES system can be used for creating additional revenues apart from peak consumption hours.

8 | Conclusion

With the goal of proposing an economically and ecologically more favourable electricity supply to the new stadium of Freiburg in Germany, a techno-economic assessment of three systems is carried out. The DG system represents the current practice of supplying the stadium with DGs during match while the rest of the time electricity is purchased from the grid. With the PVDG system a PV plant is added, from which electricity is consumed directly by the stadium, while excess electricity is fed into the grid or sold on the electricity market. Finally, the PVBES system offers a concept without diesel units, where the stadium's supply is covered with a Li-Ion battery storage.

8.1 Results of the systems

The results from the DG system (Chapter 3) clearly show a high net cost after the 20 years time horizon, as it can be seen in Figure 8.1.

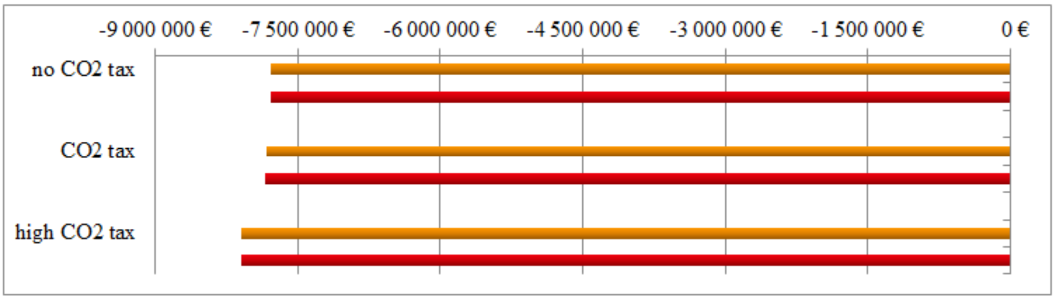

Figure 8.1: NPC results DG system (orange - Case 1 results, red - Case 2 results) (*own illustration and calculations*)

The PVDG system (Chapter 4) offers a far better economic option given the potential revenues that are created by selling excess electricity from the PV plant. Even with the considered CO_2 tax the NPC is less than half the amount of the DG system's NPC.

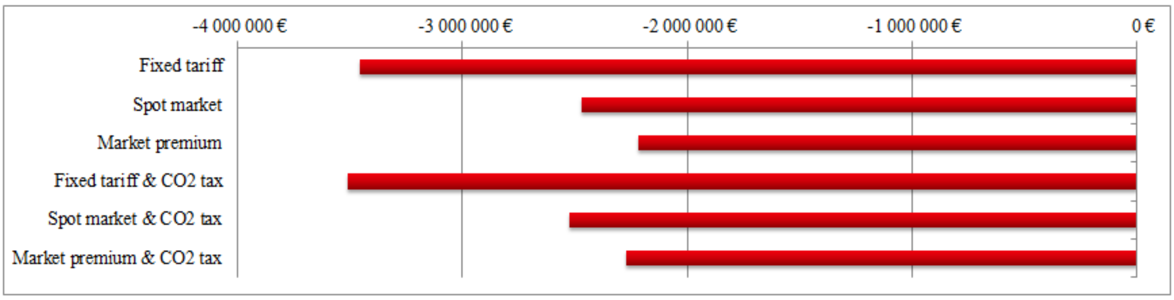

Figure 8.2: NPC results of the PVDG system including CO_2 tax

The reason for the much higher NPC of the fixed tariff scenario is due to the fact that electricity prices are much higher than the received FIT for a power plant of this size. Nevertheless, the investment is never amortised. Additionally, despite less electricity consumption from the grid which is supplied by both RE and fossil fuels, the DG units still operate during the match and thus the emissions of 30 tCO_2e/year remain unchanged in both systems.

With the PVBES system (Chapter 5) a more flexible trading can be carried out on the market where higher revenues can be achieved. Nevertheless, neither by trading on the spot market nor with addition of a market premium pay back the high investment costs of the system. Various scenarios were considered, like different PV capacities which do not result in a lower NPC than the PVDG system. Smaller battery capacities result in more favourable NPCs, with the 2 MWh battery being even lower than the PVDG system. Even with a capacity of 3 MWh, an almost similar NPC is achieved. It can be concluded that if the regulations for the electricity supply of match in a stadium are altered or neglected, lower battery capacities would suffice for replacing the DG unit and thus offer an economically more favourable option to the stadium operator than the use of DGs. Finally, with lower battery prices that are predicted to be reached by 2030, the PVBES system offers the economically most favourable option to the stadium operator.

For achieving a positive NPV with the PVBES system, more economic scenarios were assessed (Chapter 6). By offering primary energy reserve on the electricity balancing market, constant revenues can be gained that are more profitable than when electricity is sold on the spot market. For the assessment a high and a low remuneration scenario were considered of which both result in a positive NPV. Furthermore, two PPAs were considered as well, with one selling excess electricity to a nearby student residence and another selling to EV charging stations located at the parking area of the stadium. While the former achieved a positive NPV, the latter did not gain enough revenues to amortise the high costs of the PVBES system. Nevertheless, by considering a combination of the two PPAs, an even higher NPV is the result.

8.2 Research questions

In this section the research question and subquestions from Chapter 1 are answered.

How can the Freiburg stadium's current electricity supply system be changed from diesel units to a utility-scale PVBES, what are the technical, economic and environmental consequences and what economic factors hamper or support this transition?

Given the requirements of the stadium operator and the available area on the rooftop of the stadium, a PV plant with 1.8 MWp power and a Li-Ion battery storage with 4 MWh capacity are chosen to replace the current practice electricity supply. With the DG system a self-reliance of 6% is given and thus, a high amount of OPEX (88%) derive from the costs of electricity purchased from the grid, whereas the self-reliance is increased to 58% with the PVDG system and even 76% with the PVBES system. Considering different economic scenarios, the PVBES system results in significantly more favourable NPVs than the DG system and can even achieve a positive NPV through trading on the electricity balancing market or by entering into a PPA. Furthermore, by replacing the diesel units with the battery, no CO_2 or GHG are emitted during the operation phase, if the electricity mix from the grid is not taken into account. It has been identified that certain measures like the EEG surcharge pose a disadvantage to the PVBES system as they make up a notable amount of the OPEX. Indeed, the self-consumption surcharge makes up 16% of the total OPEX in a year when a fixed tarrif scenario is considered. Furthermore, the expenses of direct trading through PPAs make a notable amount of the outgoing CFs, with 59% being paid for direct trading and 18% for the self-consumption surcharge (PPA with student residence scenario). The CFs of the economic scenarios are shown in Figure 8.3 compared to the market premium scenario.

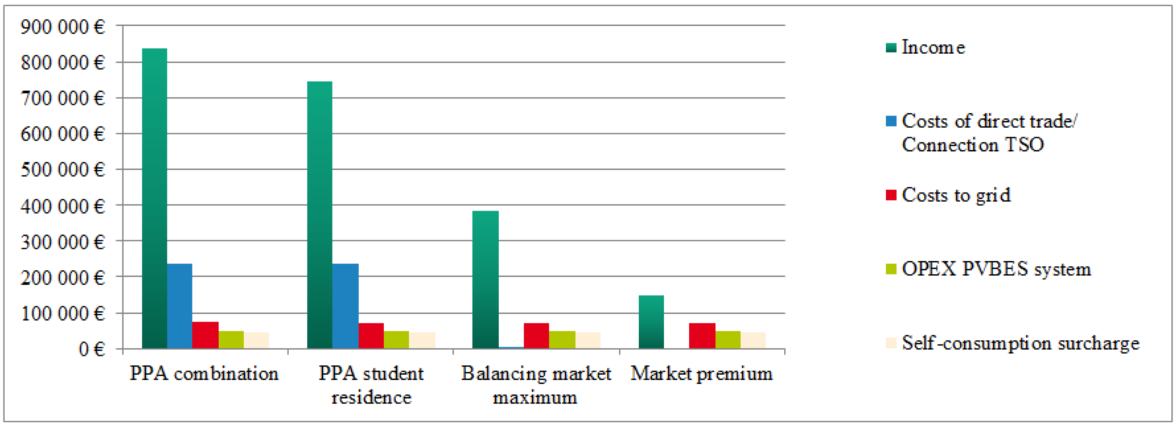

Figure 8.3: CFs of four PVBES scenarios compared

It can be seen that the costs of direct trade for the two PPA scenarios strongly outweigh the other costs. However, given that the income is tremendously higher, this high cost does not pose a notable disadvantage to the economic feasibility. Furthermore, given that these expenses flow into the EEG budget, it could be argued that the outgoing money is used to finance transitions from fossil fuel based units to RE power plants. Therefore, this factor should be viewed rather as an opportunity for more systems like the one proposed, as costs for grid expansion or curtailment would decrease and the money saved can be used to finance the investment costs of the proposed system.

What is the stadium's electricity supply with only DGs, what are the costs for the system and how high are the CO_2 emissions? It is identified in Chapter 3 that the DGs only cover around 6% or 90 MWh of the total annual load of the stadium. The base load is supplied by the grid in exchange for the average industry price in Germany as of 2018. Figure 8.4 compares the amount of load covered by the different units.

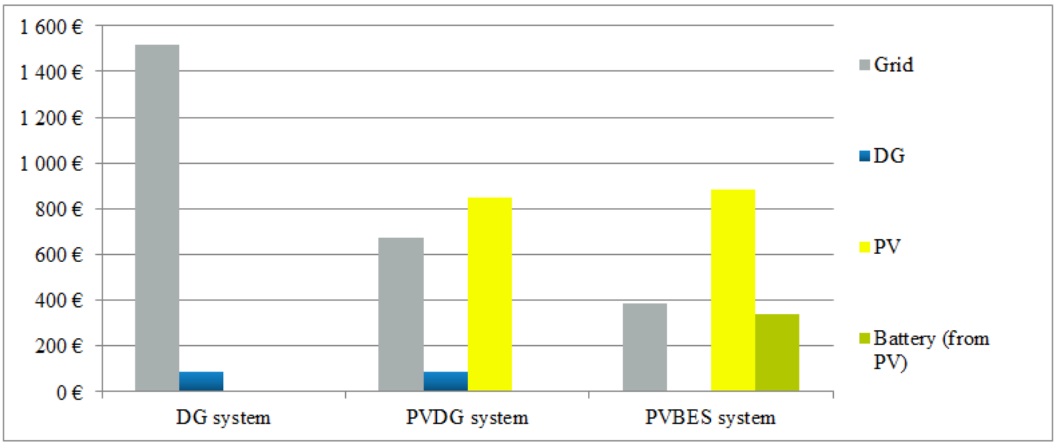

Figure 8.4: Amount of load covered by the different units within the different systems

The expenditures for electricity obtained from the grid make up 88% of the total expenses to supply the annual electricity load of the stadium. CO_2 emissions are calculated as CO_2 equivalent and determined to be 30t of CO_2 emissions per year.

How can a utility-scale PV plant combined with battery storage replace the DGs, supply the stadium in Freiburg and what is the economic feasibility? This is answered in Chapter 5, where the techno-economic feasibility of the PVBES system is determined. Different economic scenarios with lower battery or PV plant capacity and lower costs are considered as well. The results show that all economic scenarios are more preferable than those of the DG system. What is more, with the right electricity trading strategy the PVBES system pays back within 8 to 16 years when balancing market trading or PPAs are considered.

What electricity selling scenarios could improve the techno-economic feasibility of this system in order to pay back the high investment and operation costs? By assessing different economic scenarios in order to achieve a positive NPV the answer to this question is given. The payback times identified are 16 years for the minimum income from the balancing market and 8 years for the maximum balancing market income considered. A PPA with the student residence nearby the stadium has a payback time of 8 years, as well as a combined PPA scenario with EV charging stations and the student residence. Figure 8.5 shows the results of all NPVs from the PVBES system.

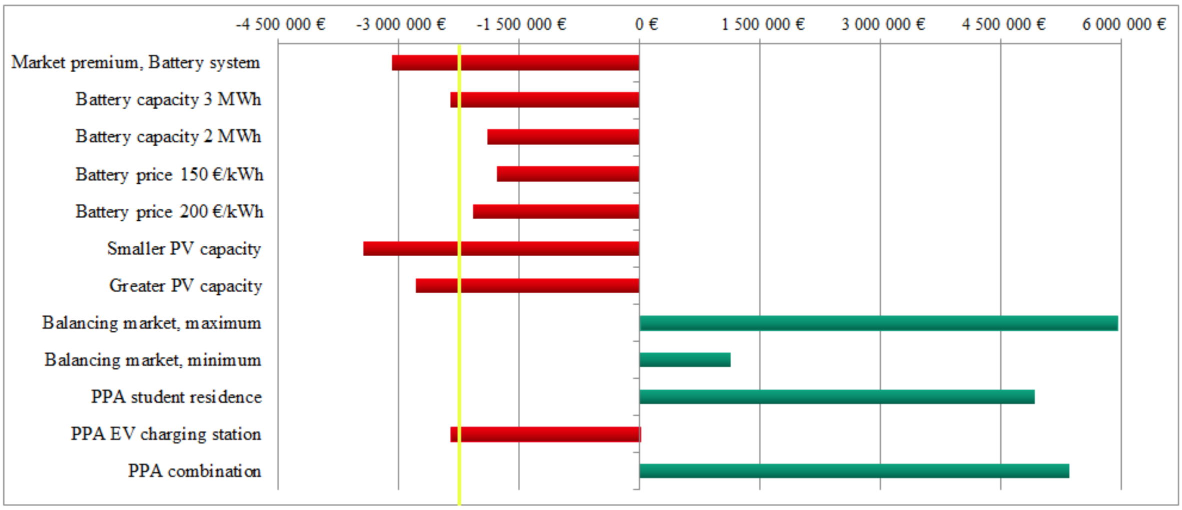

Figure 8.5: NPV of all economic scenarios of the PVBES system calculated with energyPRO compared to the NPC of the PVDG system with market premium scenario indicated by the yellow line

What are the environmental benefits in terms of CO_2 emissions during operation? The answer is found with the proposition of the PVBES system in Chapter 5, as the system has no CO_2 emissions during operation. This means that without the use of DGs, 30 tonnes of CO_2e are saved every year. Nevertheless, by carrying out a complete LCA of the three systems, a more accurate conclusion could be provided concerning the environmental benefits.

In the discussion of the generalisability of the work, it should be kept in mind that the outcome is applicable in a German context only. Factors like charges and taxes apply for Germany, therefore the resulting CFs cannot be considered for cases in other countries.

8.3 Future outlook

It is expected that the number of utility-scale PVBES will increase in the future, given the economic potential in Germany. This development will make way to new business concepts like PPAs, but also make use of strategies that are already common for BESS operators, like offering a reserved load to the balancing market. As prices are expected to drop further for both PV plants and BESS, especially Li-Ion, the economic feasibility is expected to improve in the following years.

Bibliography

[1] European Environmental Agency. *Sectoral greenhouse gas emissions by IPCC sector*. 2016. URL: https://www.eea.europa.eu/data-and-maps/daviz/change-of-co2-eq-emissions-2#tab-dashboard-01 (visited on 04/02/2019).

[2] V. Krey et al. "Getting from here to there – energy technology transformation pathways in the EMF27 scenarios". In: *Climatic Change* 123.3 (2014), pp. 369–382. ISSN: 1573-1480. DOI: {10.1007/s10584-013-0947-5}. URL: https://doi.org/10.1007/s10584-013-0947-5.

[3] Yadack M. Boch P. Eicker U. and M. Brennenstuhl. *Netzintegration von Photovoltaik im städtischen Raum bis 2050*. 2017, pp. 54–56. (Visited on 02/25/2019).

[4] R. Lacal Arantegui and A Jäger-Waldau. "Photovoltaics and wind status in the European Union after the Paris Agreement". In: *Renewable and Sustainable Energy Reviews* 81 (2018), pp. 2460–2471. DOI: {10.1016/j.rser.2017.06.052}.

[5] Zerzawy F. Sax A. Veit K. Fiedler S. and Klinski S. "Alternative Finanzierungsoptionen für erneuerbare Energien im Kontext des Klimaschutzes und ihrer zunehmenden Bedeutung über den Stromsektor hinaus". In: *CLIMATE CHANGE 20/2018* (2019). Ed. by Forum Ökologisch-Soziale Marktwirtschaft e.V. Umweltbundesamt (UBA). (Visited on 04/29/2019).

[6] B. Burger. *Energy Charts*. Freiburg, 2019. URL: https://energy-charts.de/.

[7] B. Burger. *Bierdeckel-Rechnung: So einfach sind 65 Prozent Erneuerbare bis 2030 erreichbar*. Ed. by S. Enkhard. pv-magazine.de, 2018. URL: https://www.pv-magazine.de/2018/11/16/bierdeckel-rechnung-so-einfach-sind-65-prozent-erneuerbare-bis-2030-erreichbar/ (visited on 06/13/2019).

[8] Agora Energiewende. "Stromnetze für 65 Prozent Erneuerbare bis 2030: Zwölf Maßnahmen für den synchronen Ausbau von Netzen und Erneuerbaren Energien". In: (2018). URL: www.agora-energiewende.de (visited on 02/26/2019).

[9] "Aktuelle Fakten zur Photovoltaik in Deutschland". In: (2019). Ed. by Wirth, H. URL: www.pv-fakten.de (visited on 02/26/2019).

[10] R. Paschotta. *Residuallast: RP-Energie-Lexikon*. URL: https://www.energie-lexikon.info/residuallast.html (visited on 03/13/2019).

[11] P.-J. Alet et al. "Quantification, challenges and outlook of PV integration in the power system: A review by the European PV Technology Platform". In: *31st European Photovoltaic Solar Energy Conference and Exhibition* (2015), pp. 2945–2951. DOI: {10.4229/EUPVSEC20152015-7EP.1.2}.

[12] Bundesnetzagentur. "Netz- und Systemsicherheitsmaßnahmen: Zweites und drittes Quartal 2018". In: (2019). (Visited on 04/22/2019).

[13] 50Hertz Transmission GmbH et al. "Netzentwicklungsplan Strom 2030, Version 2019: Erster Entwurf der Übertragungsnetzbetreiber". In: (2019). URL: www.netzentwicklungsplan.de (visited on 05/29/2019).

[14] Verband der Elektrotechnik VDE, Energietechnische Gesellschaft. "Batteriespeicher in der Nieder- und Mittelspannungsebene Anwendungen und Wirtschaftlichkeit sowie Auswirkungen auf die elektrischen Netze". In: (2015), 1–199. URL: https://speicherinitiative.at/assets/Uploads/03-Batterienspeicher.pdf (visited on 02/28/2019).

[15] EEM Energy & Environment Media GmbH. and pvXchange. *Photovoltaik Preise: PVX Spotmarkt Preisindex auf dem Solarserver*. Ed. by pvxchange.com. 2019. URL: https://www.solarserver.de/service-tools/photovoltaik-preisindex.html (visited on 04/02/2019).

[16] Kost, C. et al. "Levelized Cost of Electricity - Renewable Energy Technologies". In: (2018). (Visited on 03/07/2019).

[17] Feldman, D., Barbose, G., Margolis, R., Bolinger, M., Chung, D., Fu, R., Seel, J., Davidson, C., Darghouth N. "Photovoltaic System Pricing Trends: Historical, Recent, and Near-Term Projections, 2015 Edition". In: (). Ed. by R. Lawrence Berkeley National Laboratory Wiser. URL: https://escholarship.org/uc/item/9pc3x32t (visited on 03/29/2019).

[18] Fraunhofer ISE and Agora Energiewende. "Current and Future Cost of Photovoltaics: Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems: Study on behalf of Agora Energiewende". In: (2015). URL: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf (visited on 03/13/2019).

[19] F. Creutzig et al. "The underestimated potential of solar energy to mitigate climate change". In: *Nature Energy* 2.9 (2017), p. 369. ISSN: 2058-7546. DOI: {10.1038/nenergy.2017.140}.

[20] Loew T. Seneviratne S. I. Lucht-W. Beck M.-L. Hesse J. Knutti R. Quaschn V. Schleimer J.-H. Mattauch L. Breyer C. Hübener H. Kirchengast G. Chodura A. Clausen J. Creutzig F. Darbi M. Daub D.-H. Ekardt F. Göpel M. Hardt J. N. Hertin J. Hickler T. Köhncke A. Köster S. Krohmer J. Kromp-Kolb H . Leinfelder R. Mederake L. Neuhaus M. Rahmstorf S . Schmidt C. Schneider C. Schneider G. Seppelt R. Spindler U. Springmann M. Staab K. Stocker T. F. Steininger K. von Hirschhausen E. Winter S. Wittau M. Hagedorn G. and J. Zens. *The concerns of the young protesters are justified A statement by Scientists for Future concerning the protests for more climate protection*. (Visited on 04/04/2019).

[21] Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg, Bosch & Partner GmbH. "Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz: Teilvorhaben II c: Solare Strahlungsenergie: Zwischenbericht, Februar 2018". In: (2018). URL: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/bmwi_de/bericht-eeg-4-solar.pdf?__blob=publicationFile&v=4 (visited on 03/13/2019).

[22] Bundesministerium für Wirtschaft und Energie. *Förderung Energiespeicher*. URL: {https://www.bmwi.de/Redaktion/DE/Artikel/Energie/foerderung-energiespeicher.html} (visited on 04/30/2019).

[23] RnR Market Research. *Lead Acid Battery Industry 2015-2018: Forecasts in New Market Research Reports*. RnR Market Research. URL: http://www.rnrmarketresearch.com/global-and-china-lead-acid-battery-industry-report-2015-2018-market-report.html (visited on 03/25/2019).

[24] A. Thielmann and Fraunhofer ISI. "Energiespeicher-Roadmap Update 2017: Hochenergie-Batterien 2030+ und Perspektiven zukünftiger Batterietechnologien". In: (2017). URL: https://batterie-2020.de/wp-content/uploads/2018/01/batterie-2020.de-energiespeicher-roadmap-2017-energiespeicher-roadmap-dezember-2017.pdf (visited on 03/25/2019).

[25] Institut für Stromrichtertechnik und Elektrische Antriebe RWTH Aachen. "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher 2.0: Jahresbericht 2018". In: *Speichermonitoring* (2018). URL: http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2018_ISEA_RWTH_Aachen.pdf (visited on 03/14/2019).

[26] Deutsche Energie Agentur dena. *Liberalisierung des Strommarktes: Weiterentwicklung des Strommarkts: Die Liberalisierung als Basis*. Ed. by dena. URL: https://www.dena.de/themen-projekte/energiesysteme/strommarkt/ (visited on 02/26/2019).

[27] eurostat. *Electricity prices for non-household consumers - bi-annual data; Germany*. 2019. URL: http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do (visited on 05/14/2019).

[28] BDEW Bundesverband der Energie- und Wasserwirtschaft e.V. "BDEW-Strompreisanalyse Januar 2019: Haushalte und Industrie". In: (2019). URL: https://www.bdew.de/media/documents/190115_BDEW-Strompreisanalyse_Januar-2019.pdf (visited on 02/26/2019).

[29] Bundesnetzagentur. "Monitoringbericht 2018: Monitoringbericht gemäß § 63 Abs. 3 i. V. m. § 35 EnWG und § 48 Abs. 3 i. V. m. § 53 Abs. 3 GWB". In: (2019). URL: https://www.bundesnetzagentur.de/DE/Sachgebiete/ElektrizitaetundGas/Unternehmen_Institutionen/DatenaustauschundMonitoring/Monitoring/Monitoringberichte/Monitoring_Berichte_node.html (visited on 05/02/2019).

[30] Bundesnetzagentur. "EEG in Zahlen 2017". In: (2017). URL: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/ErneuerbareEnergien/ZahlenDatenInformationen/EEGinZahlen_2017_BF.pdf?__blob=publicationFile&v=2 (visited on 03/12/2019).

[31] Kathrin Graulich and Öko-Institut e.V. "Einsatz und Wirtschaftlichkeit von PV-Batteriespeichern in Kombination mit Stromsparen: Kurzinformation für Verbraucherinnen und Verbraucher". In: (2018). URL: https://www.oeko.de/fileadmin/oekodoc/PV-Batteriespeicher-ETT-Information.pdf (visited on 03/14/2019).

[32] Umweltministerium Baden-Württemberg. "Publikation: Photovoltaik und Batteriespeicher; Technologie, Integration, Wirtschaftlichkeit". In: (2017). URL: https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/2_Presse_und_Service/Publikationen/Energie/UM_PV_Batteriespeicher.pdf (visited on 03/13/2019).

[33] next Kraftwerke. *Virtuelles Kraftwerk | Direktvermarkter | Stromhändler*. 2019. URL: https://www.next-kraftwerke.de/ (visited on 05/28/2019).

[34] Institut für Sportstättenberatung GmbH. *DAS NEUE STADION FREIBURG*. 2019. URL: http://www.ifs-sport.de/de/projekt-stadion/alias/das-neue-stadion-freiburg.html (visited on 05/06/2019).

[35] Mithulananthan N. Bansal R. C. Ramachandaramurthy V.K. Shah R. "A review of key power system stability challenges for large-scale PV integration". In: *Renewable and Sustainable Energy Reviews* 41 (2015), pp. 1423–1436. DOI: {10.1016/j.rser.2014.09.027}.

[36] R. Gómez T. Prettico G . Frías P.-Fulli G. Meletiou A. Mateo C. Cossent and F. Postigo. "Impact of solar PV self-consumption policies on distribution networks and regulatory implications". In: *Solar Energy* 176 (2018), pp. 62–72. DOI: {10.1016/j.solener.2018.10.015}.

[37] Frías P. Cossent R. Sonvilla P. Mateo C. and B. Barth. "Overcoming the barriers that hamper a large-scale integration of solar photovoltaic power generation in European distribution grids". In: *Solar Energy* 153 (2017), pp. 574–583. DOI: {10.1016/j.solener.2017.06.008}.

[38] K. Creutzig F . Schl ömer S. Edenhofer O. Seyboth. "On the Sustainability of Renewable Energy Sources". In: *Annual Review of Environment and Resources* 38.1 (2013), pp. 169–200. DOI: {10.1146/annurev-environ-051012-145344}.

[39] Krey V. Calvin K. Merrick J. Mima S. Pietzcker-R. Van Vliet J. Luderer G. and K. Wada. "The role of renewable energy in climate stabilization: Results from the EMF27 scenarios". In: *Climatic Change* 123.3 (2014), pp. 427–441. ISSN: 1573-1480. DOI: {10.1007/s10584-013-0924-z}. URL: https://doi.org/10.1007/s10584-013-0924-z.

[40] C. Breyer et al. "On the role of solar photovoltaics in global energy transition scenarios". In: *Progress in Photovoltaics: Research and Applications* 25.8 (2017), pp. 727–745. DOI: {10.1002/pip.2885}.

[41] Burger, B. "Öffentliche Nettostromerzeugung in Deutschland im Jahr 2018". In: (2019). URL: https://www.ise.fraunhofer.de/content/dam/ise/de/documents/news/2019/Stromerzeugung_2018_3.pdf (visited on 04/17/2019).

[42] Klima-Allianz Deutschland. "WANN, WENN NICHT JETZT: Das Maßnahmenprogramm Klimaschutz 2030 der deutschen Zivilgesellschaft". In: (2018). URL: https://www.klima-allianz.de/fileadmin/user_upload/Ma{\%}C3{\%}9Fnahmenprogramm2030_web.pdf (visited on 04/05/2019).

[43] H.-M. Henning and A. Palzer. "Energiesystem Deutschland 2050". In: *Erneuerbare Energie: EE, (2014), No.2, pp.4-7* (2014).

[44] J. N. Mayer. "Projektstudie für zukünftige Systemtechnik und Netzanbindung regenerativer Kraftwerke". Diplomarbeit. Universität Ulm. (Visited on 02/28/2019).

[45] H.-M. Henning and A. Palzer. *Was kostet die Energiewende? Wege zur Transformation des deutschen Energiesystems bis 2050*. Fraunhofer ISE, 2015.

[46] B. Plangklang, N. Thanomsat, and T. Phuksamak. "A verification analysis of power quality and energy yield of a large scale PV rooftop". In: *Energy Reports* 2 (2016), pp. 1–7. DOI: {10.1016/j.egyr.2015.12.002}.

[47] Bergner J. Siegel B. and Quaschning.V. "PV in Städten – Erkenntnisse über Potenziale und Hürden in Berlin". In: *32. Symposium Photovoltaische Solarenergie. Kloster Banz, Bad Staffelstein* (2017). (Visited on 02/25/2019).

[48] Geldermann J. Bertsch V. and Lühn T. "What drives the profitability of household PV investments, self-consumption and self-sufficiency?" In: *Applied Energy* 204 (2017), pp. 1–15. DOI: {10.1016/j.apenergy.2017.06.055}.

[49] Castillo-Cagigal M. Matallanas E. Caamaño-Martín E. Calpa M. and A. Gutiérrez. "Effects of Large-scale PV Self-consumption on the Aggregated Consumption". In: *Procedia Computer Science* 83 (2016), pp. 816–823. DOI: {10.1016/j.procs.2016.04.171}.

[50] Hoet-B. Jacqmin J. Gautier A. and S. Van Driessche. "Self-consumption choice of residential PV owners under net-metering". In: *Energy Policy* 128 (2019), pp. 648–653. DOI: {10.1016/j.enpol.2019.01.055}.

[51] J. von Appen and M. Braun. "Interdependencies between self-sufficiency preferences, techno-economic drivers for investment decisions and grid integration of residential PV storage systems". In: *Applied Energy* 229 (2018), pp. 1140–1151. DOI: {10.1016/j.apenergy.2018.08.003}.

[52] F. Javier Ramírez et al. "Combining feed-in tariffs and net-metering schemes to balance development in adoption of photovoltaic energy: Comparative economic assessment and policy implications for European countries". In: *Energy Policy* 102 (2017), pp. 440–452. DOI: {10.1016/j.enpol.2016.12.040}.

[53] A. Zucker and T. Hinchliffe. "Optimum sizing of PV-attached electricity storage according to power market signals – A case study for Germany and Italy". In: *Applied Energy* 127 (2014), pp. 141–155. DOI: 10.1016/j.apenergy.2014.04.038.

[54] M. Schachinger. *Der Schweinezyklus: Und ewig grüßt das Murmeltier: Steht uns nach der Erholung schon wieder ein größerer Markteinbruch in Deutschland bevor?* pv-magazine.de, 2019. URL: https://www.pv-magazine.de/2019/02/19/der-schweinezyklus/ (visited on 03/29/2019).

[55] pvEurope. *1.5 MW PV rooftop system in Sweden*. Ed. by Alfons W. Gentner Verlag GmbH & Co. KG. 2018. (Visited on 03/19/2019).

[56] pvEurope. *IBC Solar: 1 MW rooftop PV plant for food cooling in Norway with self-consumption*. 2016. (Visited on 03/19/2019).

[57] SolarServer. *Canadian Solar und Green City Energy schließen Photovoltaik-Großprojekt in Sachsen in Rekordzeit ab*. Ed. by EEM Energy & Environment Media GmbH. 2010. (Visited on 03/19/2019).

[58] Klima- und Energiefonds Work Group. "Abschlussbericht der Speicherinitiative Startphase: Zusammengestellt auf Basis der Ergebnisse aus den sechs Arbeitsgruppen: Soeicherinitiative". In: (2016). (Visited on 03/25/2019).

[59] J. Büngeler et al. "Advantages in energy efficiency of flooded lead-acid batteries when using partial state of charge operation". In: *Journal of Power Sources* 375 (2018), pp. 53–58. DOI: {10.1016/j.jpowsour.2017.11.050}.

[60] R. Sterrer and W. Prüggler. "Multifunktionales Batteriespeichersystem". In: *e & i Elektrotechnik und Informationstechnik* 130.6 (2013), pp. 161–168. DOI: {10.1007/s00502-013-0148-y}.

[61] Zhang-J. Kintner-Meyer M. C. W. Lu X.-Choi D. Lemmon J. P. Yang Z. and J. Liu. "Electrochemical energy storage for green grid". In: *Chemical reviews* 111.5 (2011), pp. 3577–3613. DOI: {10.1021/cr100290v}.

[62] Guo-S. Zhao H. and H. Zhao. "Comprehensive Performance Assessment on Various Battery Energy Storage Systems". In: *Energies* 11.10 (2018), p. 2841. DOI: {10.3390/en11102841}.

[63] Six-D. Claessens-B. Broes T. Omar N. Mulder G. and J. Van Mierlo. "The dimensioning of PV-battery systems depending on the incentive and selling price conditions". In: *Applied Energy* 111 (2013), pp. 1126–1135. DOI: {10.1016/j.apenergy.2013.03.059}.

[64] Papaioannou-I. T. Purvins A. and L. Debarberis. "Application of battery-based storage systems in household-demand smoothening in electricity-distribution grids". In: *Energy Conversion and Management* 65 (2013), pp. 272–284. DOI: {10.1016/j.enconman.2012.07.018}.

[65] McManus-M. Cooper-S. McKenna E. and M. Thomson. "Economic and environmental impact of lead-acid batteries in grid-connected domestic PV systems". In: *Applied Energy* 104 (2013), pp. 239–249. DOI: {10.1016/j.apenergy.2012.11.016}.

[66] D'Adamo I. Cucchiella F. and M. Gastaldi. "The Economic Feasibility of Residential Energy Storage Combined with PV Panels: The Role of Subsidies in Italy". In: *Energies* 10.9 (2017), p. 1434. DOI: {10.3390/en10091434}. (Visited on 06/11/2019).

[67] Schweer D. Stein-D. von Moser A. Thien T. and D. U. Sauer. "Real-world operating strategy and sensitivity analysis of frequency containment reserve provision with battery energy storage systems in the german market". In: *Journal of Energy Storage* 13 (2017), pp. 143–163. DOI: {10.1016/j.est.2017.06.012}.

[68] Jin Y.G. Kim H. T. and Yoon Y. T. "An Economic Analysis of Load Leveling with Battery Energy Storage Systems (BESS) in an Electricity Market Environment: The Korean Case". In: *Energies* 12.9 (2019), p. 1608. DOI: {10.3390/en12091608}. (Visited on 06/11/2019).

[69] Delta Electronics (Netherlands) B.V. *Kaohsiung World Stadium, Taiwan: Realizing huge PV plants with small inverters*. (Visited on 03/19/2019).

[70] Sun&WindEnergy Hg. v. VDE VERLAG GMBH, zuletzt geprüft am 19.03.2019. *India's first 1 MW rooftop PV plant*. Ed. by VDE VERLAG GMBH. (Visited on 03/19/2019).

[71] Weiß V. Stahl W. "Energieversorgung Neubau SC Stadion Freiburg: Vorkonzept + Ergänzungen". In: (2015). URL: https://www.freiburg.de/pb/site/Freiburg/get/params_E1585085054/1109158/Fortschreibung_Energiekonzept_Stadion.pdf (visited on 05/06/2019).

[72] The Mobility House. *The 3 megawatt energy storage system in Johan Cruijff ArenA is now live*. 2018. URL: https://www.mobilityhouse.com/int_en/magazine/press-releases/johan-cruijff-arena-3mw-energy-storage-system-launch.html (visited on 06/11/2019).

[73] R. Knauer. "Ende der Dauerbrenner: Energiewende: Wie gelingt die Dezentralisierung der Energieversorgung?" In: *Spektrum der Wissenschaft* 16/2018 (). URL: https://www.spektrum.de/news/energiewende-wie-gelingt-die-dezentralisierung-der-energieversorgung/1558698 (visited on 03/13/2019).

[74] H. Lund. "Choice awareness: the development of technological and institutional choice in the public debate of Danish energy planning". In: *Journal of Environmental Policy and Planning* 2.3 (2000), pp. 249–259. DOI: {10.1002/1522-7200(200007/09)2:3{\textless}249::AID-JEPP50{\textgreater}3.0.CO;2-Z}.

[75] Influence Map. "An investor enquiry: how much big oil spends on obstructive climate lobbying". In: (2016). URL: https://influencemap.org/site/data/000/173/Lobby_Spend_Report_March_2016.pdf (visited on 06/10/2019).

[76] H. Lund. "Methodology: Choice Awareness Strategies". In: *Renewable Energy Systems*. Elsevier, 2014, pp. 35–51. ISBN: 9780124104235. DOI: {10.1016/B978-0-12-410423-5.00003-1}.

[77] R. K. Yin. *Case Study Research and Applications: Design and Methods*. SAGE Publications, 2017. ISBN: 9781506336183. URL: https://books.google.de/books?id=6DwmDwAAQBAJ.

[78] B. Flyvbjerg. "Five Misunderstandings About Case-Study Research". In: *Qualitative Inquiry* 12.2 (2016), pp. 219–245. DOI: 10.1177/1077800405284363.

[79] M. S. Morgan. "Exemplification and the use-values of cases and case studies". In: *Studies in History and Philosophy of Science Part A* (2018). DOI: {10.1016/j.shpsa.2018.12.008}.

[80] Lund H. Hvelplund F. and D. Sukkumnoed. "Feasibility studies and technological innovation". In: *Tools for Sustainable Development* (2007), pp. 593–618.

[81] Microsoft Office. *Übersicht über Formeln in Excel*. 2019. (Visited on 05/23/2019).

[82] Gilman P. Lambert T. and P. Lilienthal. "Micropower System Modeling with HOMER". In: *Farret F. A. and Godoy Sim, M: Integration of Alternative Sources of Energy.* (2006), pp. 379–418. URL: https://www.homerenergy.com/documents/MicropowerSystemModelingWithHOMER.pdf (visited on 03/27/2019).

[83] EMD International. *Modules - EMD International A/S*. 2019. URL: https://www.emd.dk/energypro-germany/module/ (visited on 05/23/2019).

[84] D. Kumar. "Economic Assessment of Photovoltaic Energy Production Prospects in India". In: *Procedia Earth and Planetary Science* 11 (2015), pp. 425–436. DOI: 10.1016/j.proeps.2015.06.042.

[85] Bergner J. Tjaden-T. Weniger J. and V. Quaschning. "Economics of residential PV battery systems in the selfconsumption age". In: *31st European Photovoltaic Solar Energy Conference and Exhibition* (). DOI: {10.4229/EUPVSEC20142014-7DO.14.3}. (Visited on 05/22/2019).

[86] investopedia. *Inflation Definition*. 2019. URL: https://www.investopedia.com/terms/i/inflation.asp (visited on 05/06/2019).

[87] Agora Energiewende. "Renewables versus fossil fuels – comparing the costs of electricity systems: Electricity system designs for 2050 – An analysis of renewable and conventional power systems in Germany". In: (2017). URL: https://www.agora-energiewende.de/en/publications/ (visited on 05/22/2019).

[88] Germany Trade and Invest. "The Energy Storage Market in Germany: Fact Sheet". In: (2019). URL: https://www.gtai.de/GTAI/Content/EN/Invest/_SharedDocs/Downloads/GTAI/Fact-sheets/Energy-environmental/fact-sheet-energy-storage-market-germany-en.pdf?v=12 (visited on 05/22/2019).

[89] Danish Energy Agency. "Technology Data Catalogue for electricity and District Heating: Lastest update February 2019". In: (2016). URL: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh_-_0001.pdf (visited on 04/17/2019).

[90] Statistisches Bundesamt. *Durchschnittlicher Preis für Dieselkraftstoff in Deutschland in den Jahren 1950 bis 2019 (Cent pro Liter)*. Ed. by statista.com. 2019. URL: https://de.statista.com/statistik/daten/studie/779/umfrage/durchschnittspreis-fuer-dieselkraftstoff-seit-dem-jahr-1950/ (visited on 04/17/2019).

[91] T. Tobiasen. "Forudsætningsnotat til Basisfremskrivning 2018". In: (). (Visited on 06/11/2019).

[92] M. Bräuninger and M. O. Teuber. "Die steuerliche Belastung von Benzin und Diesel: Fakten und Analysen". In: (2017). URL: https://www.afm-verband.de/files/2714/9855/4362/MEW_Studie_01_17_Komplett.pdf (visited on 04/05/2019).

[93] Photon Solar Energy Germany. "PHOTON SOLAR SC-LINE: SC-310M". In: (). (Visited on 05/13/2019).

[94] IRENA/Renewables Academy. "Economic assessment of PV and wind for energy planning". In: (). (Visited on 04/30/2019).

[95] P. Larsson and P. Börjesson. "Cost models for battery energy storage systems". Bachelor of Science Thesis. Stockholm, Sweden: KTH, 2018. (Visited on 04/30/2019).

[96] V. Jülch. "Comparison of electricity storage options using levelized cost of storage (LCOS) method". In: *Applied Energy* 183 (2016), pp. 1594–1606. DOI: {10.1016/j.apenergy.2016.08.165}.

[97] pv magazine.de. *Direktvermarktung lohnt sich und ermöglicht neue Geschäftsmodelle*. 2017. URL: https://www.pv-magazine.de/2017/11/20/direktvermarktung-lohnt-sich-und-ermoeglicht-neue-geschaeftsmodelle/ (visited on 06/03/2019).

[98] regelleistung.net. *Ausschreibungskalender*. 2019. URL: https://www.regelleistung.net/ext/calendar/tender (visited on 06/03/2019).

[99] EUWID Neue Energie. *Geschäftsmodell Power Purchase Agreement (PPA): Potenzial zum Megatrend? | EUWID Neue Energie Nachrichten*. 2019. URL: https://www.euwid-energie.de/geschaeftsmodell-power-purchase-agreement-ppa-potenzial-zum-megatrend/ (visited on 06/09/2019).

[100] ADAC. *Elektroautos: Ladestationen, Preise, Stromanbieter | ADAC*. 2019. URL: https://www.adac.de/rund-ums-fahrzeug/e-mobilitaet/laden/elektroauto-ladesaeulen-strompreise/ (visited on 05/27/2019).

[101] VAG Freiburg. *Park + Ride - ideale Verbindung*. 2019. URL: https://www.vag-freiburg.de/park-ride (visited on 05/27/2019).

[102] C. Csiszár. "Demand Calculation Method for Electric Vehicle Charging Station Locating and Deployment". In: *Periodica Polytechnica Civil Engineering* (2015). DOI: {10.3311/PPci.13330}. (Visited on 06/03/2019).

[103] L. Mathieu. "Roll-out of public EV charging infrastructure in the EU: Is the chicken and egg dilemma resolved?" In: (2018). (Visited on 06/03/2019).

[104] BDEW. *Standardlastprofile Strom*. 1999. URL: https://www.bdew.de/energie/standardlastprofile-strom/ (visited on 05/14/2019).

[105] L. P. Singh, S. Singh, and P. A. Bhardwaj. *Humanizing work and work Environment (HWWE 2016): English*. GIAP Journals, 2018. ISBN: 9789383006816. URL: https://books.google.de/books?id=zlJKDwAAQBAJ.

[106] J. Greenaway. "Diesel generator set QSK60 series engine: 1400 kVA-2500 kVA 50 Hz Emissions regulated". In: (2017). (Visited on 05/28/2019).

[107] World Nuclear Association. *Heat values of various fuels - World Nuclear Association*. 2019. URL: http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx (visited on 05/06/2019).

[108] Carbon Footprint. *2018 Defra Greenhouse Gas Emissions Factors*. 2018. (Visited on 05/06/2019).

[109] EMD International. *energyPRO Time Series*. 2018.

[110] NMAA. *Photovoltaik Freiburg im Breisgau » Firmen, Rechner & Angebote*. 2019. URL: https://www.rechnerphotovoltaik.de/photovoltaik/in/baden-wuerttemberg/freiburg-im-breisgau (visited on 05/29/2019).

[111] L. Unterreiner, V. Jülch, and S. Reith. "Recycling of Battery Technologies – Ecological Impact Analysis Using Life Cycle Assessment (LCA)". In: *Energy Procedia* 99 (2016), pp. 229–234. DOI: {10.1016/j.egypro.2016.10.113}.

[112] Cong T.N. Yang-W. Tan C. Li Y. Chen H. and Ding Y. "Review". In: *Progress in Natural Science: Materials International* 19.3 (2009), pp. 291–312. DOI: {10.1016/j.pnsc.2008.07.014}.

[113] EUWID Neue Energie. *VoltStorage bietet Heimspeicher mit VRF-Technologie für rund 1.000 € je kWh | EUWID Neue Energie Nachrichten*. 2018. URL: https://www.euwid-energie.de/voltstorage-bietet-heimspeicher-mit-vrf-technologie-fuer-rund-1-000-e-je-kwh/ (visited on 05/31/2019).

[114] J. Garche. "Elektrochemische Speicher für Regenerative Energien und Netzlastmanagement". In: (2012). URL: https://www.dlr.de/tt/Portaldata/41/Resources/dokumente/ess_2012/Garche_Elektrochemische_Speicher.pdf (visited on 06/03/2019).

[115] K. Khan et al. "PKL Electrochemical Cell and the Peukert's Law". In: *International Journal Of Advance Research And Innovative Ideas In Education* 4 (Apr. 2018), pp. 4219–4227.

[116] C. Brandstätt et al. *Innovation Energiespeicher: Chancen der deutschen Industrie*. Vol. Nr. 404 (November 2018). Forschungsförderung. Düsseldorf: Hans-Böckler-Stiftung, 2018. (Visited on 04/30/2019).

[117] Tsiropoulos, J., Tarvydas, D., Lebedeva, N. "Li-ion batteries for mobility and stationary storage applications: Scenarios for costs and market growth - Study". In: (2018). DOI: 10.2760/87175.

[118] J. N. Mayer and B. Burger. "Kurzstudie zur historischen Entwicklung der EEG-Umlage". In: (2014). (Visited on 06/12/2019).

[119] Ökostromanbieter. *EEG-Umlage sinkt ab 2023*. 2019. URL: https://www.oekostromanbieter.org/oekostromanbieter-blog/141-eeg-umlage-sinkt-ab-2023.html (visited on 06/12/2019).

[120] W. (ed.) Clark. *Climate Preservation in Urban Communities Case Studies*. Butterworth-Heinemann, 2019. ISBN: 978-0-12-815920-0.

[121] Alternative Energy Tutorials. *Pumped Hydro Storage - The Ups and Downs of Water*. URL: http://www.alternative-energy-tutorials.com/energy-articles/pumped-hydro-storage.html (visited on 06/13/2019).

[122] Abe, J.O. et al. "Hydrogen energy, economy and storage: Review and recommendation". In: *International Journal of Hydrogen Energy* 44.29 (2019), pp. 15072–15086. ISSN: 0360-3199. DOI: {10.1016/j.ijhydene.2019.04.068}. URL: http://www.sciencedirect.com/science/article/pii/S036031991931465X.

[123] Liu, Z. et al. "Energy storage capacity optimization for autonomy microgrid considering CHP and EV scheduling". In: *Applied Energy* 210 (2018), pp. 1113–1125. ISSN: 03062619. DOI: 10.1016/j.apenergy.2017.07.002. URL: http://www.sciencedirect.com/science/article/pii/S0306261917308656.