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Stationary Lithium-Ion Battery Energy Storage Systems
A Multi-Purpose Technology

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Executive Summary

As a result of the acceleration of the energy transition toward 100 % renewables worldwide, the existing structures in electricity networks are drastically changing, and there are entirely new demands on both, network- and system stability. Flexibility through storage is one of the most promising technology developments to counter the emerging problems. Due to the sharp fall in prices and outstanding technical characteristics, lithium-ion battery energy storage systems promise to be a cost-effective option for providing the needed flexibility.

Installations of stationary battery energy storage systems are mostly operated exclusively in a single application. As of today, the majority of applications for battery storage in Germany consist of systems increasing a single-family households' self-consumption and systems which are designed to solely serve network purposes (for instance, to participate in the market for primary control reserve). However, the results of this thesis indicate that the stacking of applications on a single system adds additional income streams making these systems economically advantageous over single systems with individual applications.

The central problems for the implementation of such multi-purpose systems are i) the regulatory frameworks for the classification and legal treatment in electricity networks and ii) the technological handling to enable simultaneous participation in multiple markets.

To overcome these problems, this thesis gives an overview of lithium-ion stationary battery storage systems, their characteristics, applications, and an outlook on promising combinations of applications in the form of case studies.

A technical framework introduces an approach for the design, implementation, and operation of a multi-purpose battery energy storage system. Finally, under the current (2017) regulatory framework in Germany, three business models for such systems are discussed.

The technological and logical implementation of multi-purpose concepts seems to be practical. Considering the characteristics of different applications as well as resulting load profiles and operating conditions, a large number of applications can be combined in a technical and economically meaningful way with one another.

The legal handling of such systems can only be seen under current regulatory context and appears to be much more complex. In particular, the legal and regulatory definition of battery storage systems in electrical networks is the greatest obstacle throughout many markets.

Multi-purpose battery energy storage systems can help answer many of the current as well as emerging problems in electricity networks. However, the interplay of larger fleets of multi-purpose battery storage systems in networks and very large system setups have yet to be investigated. In particular, it is recommended to work on new standards for the operation and definition of multi-purpose battery storage systems in electricity networks.

Kurzfassung

Durch die Beschleunigung der Energiewende auf 100% erneuerbare Energien weltweit verändern sich die bestehenden Strukturen in den Stromnetzen drastisch, und es gibt völlig neue Anforderungen an die Netzwerk- und Systemstabilität. Flexibilität durch Speicherung von elektrischer Energie ist eine der vielversprechendsten technologischen Entwicklungen, um den aufkommenden Problemen entgegenzuwirken. Aufgrund des starken Preisverfalls und der herausragenden technischen Eigenschaften versprechen Lithium-Ionen-Batterie-Energiespeichersysteme eine kostengünstige Möglichkeit, die benötigte Flexibilität bereitzustellen.

Installationen von stationären Batteriespeichersystemen werden meist ausschließlich in einer einzigen Anwendung betrieben. Die Mehrheit der Anwendungen für die Batteriespeicher in Deutschland genutzt werden besteht aus Systemen, welche den Eigenverbrauch von Einfamilienhäuser erhöhen und Systemen die ausschließlich für Netzwerkzwecke eingesetzt werden sind (z.B. die Teilnahme am Priämarregelleistungsmarket) . Die Ergebnisse dieser Arbeit zeigen jedoch, dass das Stapeln von Anwendungen auf einem einzigen System zusätzliche Einkommensströme hinzufügt, die diese Systeme gegenüber einzelnen Systeme mit individuellen Anwendungen wirtschaftlich vorteilhaft machen.

Die zentralen Probleme bei der Umsetzung solcher Mehrzweck-Systeme sind i) die regulatorischen Rahmenbedingungen für die Einstufung und rechtliche Behandlung in Elektrizitätsnetzen und ii) die technologische Abwicklung, um die gleichzeitige Teilnahme an mehreren Märkten zu ermöglichen.

Um diese Probleme zu überwinden, gibt diese Arbeit einen Überblick über Lithium-Ionen-stationäre Batteriespeichersysteme, deren Eigenschaften, Anwendungen und einen Ausblick auf vielversprechende Kombinationen von Anwendungen in Form von Fallstudien.

Ein technischer Rahmen stellt einen Ansatz für die Konzeption, Implementierung und den Betrieb eines Mehrzweck-Batteriespeichersystems vor. Schließlich werden beispielhaft unter dem derzeitigen Regulierungsrahmen (2017) in Deutschland drei Geschäftsmodelle für solche Systeme diskutiert.

Die technologische und logische Umsetzung von Mehrzweckkonzepten scheint praktisch zu sein. Unter Berücksichtigung der Eigenschaften unterschiedlicher Anwendungen sowie daraus resultierender Lastprofile und Betriebsbedingungen können eine Vielzahl von Applikationen technisch und wirtschaftlich sinnvoll miteinander kombiniert werden.

Die rechtliche Handhabung solcher Systeme ist nur unter dem aktuellen regulatorischen Kontext zu sehen und scheint viel komplexer zu sein. Insbesondere die rechtliche und regulatorische Definition von Batteriespeichersystemen in elektrischen Netzen ist das größte Hindernis in vielen Märkten.

Mehrzweck Batterie-Energiespeichersysteme können dazu beitragen, viele der aktuellen sowie aufkommende Probleme in Stromnetzen zu lösen. Allerdings ist das Zusammenspiel von größeren Flotten von Mehrzweck-Batteriespeichern in Netzwerken und sehr großen Systemen noch zu untersuchen. Insbesondere wird empfohlen, an neuen Standards für den Betrieb und die Definition von Mehrzweck-Batteriespeichern in Stromnetzen zu arbeiten.

List of Publications

Selection of Conference Contributions

M. Müller, A. Jossen, Energy Storage as a Key Enabler of a New Electrification Wave. A Battery Storage Perspective, 1st Transatlantic Perspectives on Energy Storage: Technology, Policy and Finance, Massachusetts Institute of Technology, Cambridge, October 2016 (Oral Presentation).

M. Müller, C. N. Truong, M. Schimpe, M. Naumann, H. C. Hesse, Fragmented Local Community Battery Storage Systems, Kraftwerk Batterie, Münster, April 2016 (Oral Presentation).

M. Müller, A. Jossen, Eigenheim, Mehrfamilienhaus, Ortsnetz - Energiewende lokal?, VDE Arbeitskreis Energietechnik, Munich, April 2016 (Oral Presentation).

M. Müller, A. Jossen, Shared Economy Approaches for Stationary Battery Storage Systems, Energy Storage Europe, Düsseldorf, March 2016 (Oral Presentation).

M. Müller, A. Jossen, Fragmentierte Ortsnetzspeicher - Kombination von Anwendungen zur ökonomischen Optimierung von Batteriespeichern in Ortsnetzen, 3. Konferenz Zukünftige Stromnetze für Erneuerbare Energien, Berlin, January 2016, (Poster & Oral Presentation).

M. Müller, A. Jossen, Batterie Großspeicher - Netzintegration, Business-Cases und Zukunftsperspektiven, 3. Kongress PV-Speichersysteme, Salzburg, November 2015 (Oral Presentation).

M. Müller, A. Jossen, EEBatt - Distributed stationary battery storage systems for the efficient use of renewable energies and support of grid stability, Batterieforum Deutschland, Berlin, January 2015 (Poster Presentation).

S. Rohr, M. Kerler, S. Burow, M. Müller, M. Lienkamp, A. Jossen, Risk Analysis of Lithium-Ion Energy Storage Systems in Grid Applications – a Norm-Based Approach, Battery Safety Conference, Washington, November 2014 (Poster Presentation).

Selection of Presentations

M. Müller, H. Gasteiger, A. Jossen, Energie lokal erzeugen, speichern und nutzen! Projekt EEBatt, Bavarian Parliament, Munich, February 2016 (Oral Presentation).

M. Müller, A. Jossen, 2nd Life - Vehicle to Grid - Speicherschwärme. Zukünftige Geschäftsmodelle, Stationäre Energiespeicher in regionalen Netzen, Regensburg, February 2016 (Oral Presentation).

M. Müller, A. Jossen, Einführung in stationäre Energiespeichertechnik, Stationäre Energiespeicher in regionalen Netzen, Regensburg, February 2016 (Oral Presentation).

M. Müller, A. Jossen, Regel- und Betriebsstrategien von Energiespeichern in Netzen - Teil III - Der Ortsnetzspeicher. Stationäre Energiespeicher in regionalen Netzen, Regensburg, February 2016 (Oral Presentation).

M. Müller, A. Jossen, Shared Economy Ansätze für BESS Business Modelle, BVES AG 1 Politik und Kommunikation, Berlin, January 2016 (Oral Presentation).

Peer-Reviewed Scientific Reports / Books (Co-Author)

VDE ETG, Batteriespeicher in der Nieder- und Mittelspannungsebene. Anwendungen und Wirtschaftlichkeit sowie Auswirkungen auf die elektrischen Netze, VDE e.V., Frankfurt am Main, May 2015 (Chapter).

J. Böttcher, P. Nagel, et. al, Batteriespeicher – Rechtliche, Technische und Wirtschaftliche Rahmenbedingungen, De Gruyter, Oldenbourg, January 2017 (Chapter).

Peer-Reviewed Journal Contributions (Co-Author)

C. N. Truong, M. Naumann, K. Ch. Ralph, M. Müller, A. Jossen, H. C. Hesse, Economics of Residential PV Battery Systems in Germany: The Case of Tesla's Powerwall, Batteries 2 (2016) 14-31. *

A. Zeh, M. Müller, H. C. Hesse, A. Jossen, R. Witzmann, Operating a Multitasking Stationary Battery Storage System for Providing Secondary Control Reserve on LV Level, Proceedings of International ETG Congress 147 (2015) 483-491.

A. Becker, H. Loges, S. Kippelt, A. Gitis, D. Echternacht, M. Müller, et al., Electricity Storage Systems in Medium- and LV Networks, Proceedings of International ETG Congress 147 (2015) 151-159.

J. Stich, M. Müller, H. C. Hesse, A. Jossen, T. Hamacher, Sustainable Power Supply Options for Large Islands – A case study for Belitung Island, IGST ASIA (2016) accepted. *

Journal Contributions and Seminars

M. Müller, Speicher 2020 - Produkte für viele Zwecke, SolarThemen 458 2016 (Interview).

M. Müller, Technische Universität Munich, Projekt EEBatt - Lokaler Speicher für erneuerbare Energien. Energy Neighbor geht in Betrieb, Munich 2015 (Lead).

M. Müller, Stationäre Energiespeicher in regionalen Netzen, OTTI Seminar, Regensburg, February 2015 (Seminar Leader).

M. Müller, Stationäre Energiespeicher in regionalen Netzen, OTTI Seminar, Regensburg, February 2016 (Seminar Leader).

Peer-Reviewed Journal Contributions (Lead Author)

M. Müller, L. Viernstein, C. N. Truong, A. Eiting, H. C. Hesse, R. Witzmann, A. Jossen, Evaluation of Grid-Level Adaptability for Stationary Battery Energy Storage System Applications in Europe, J. Energy Storage 8 (2016). *

M. Müller, A. Zeh, M. Naumann, H. C. Hesse, A. Jossen, R. Witzmann, Fundamentals of Using Battery Energy Storage Systems to Provide Primary Control Reserves in Germany, Batteries 2 (2016) S. 29. *

M. Müller, A. Zeh, S. Rohr, S. F. Schuster, C. Campestrini, H. C. Hesse et al.: Evaluation of the Aging Behaviour of Stationary Lithium-Ion Battery Storage Systems for Different PV-Driven Applications in Low Voltage Grids. 31st European PV Solar Energy Conference and Exhibition (2015), 3084-3090. *

** Self-produced sections of publications are partially contained in this doctoral thesis without any further reference in the running text (figures are continuously referenced).*

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1 Introduction

First, the issues examined in this thesis are placed in context. Then, a comprehensive review of prior and recent knowledge regarding stationary battery storage systems is provided to emphasize the central theme, which is the current situation in the energy market and technology and the present challenges for improving and adoption stationary battery energy storage technology. From this information, the hypothesis of this thesis is derived, and the research procedures are presented.

1.1 Motivation

The electricity industry is undergoing a major change that other sectors, for example, communications and computing, have already experienced. A major challenge in the 21st century is to ensure energy provision and safety in a clean and reliable way. The awareness of climate change and the impact of exploiting fossil fuel resources in our daily lives are increasing [1–3]. Politicians worldwide have reacted to the challenges and the protection of nature via large-scale arrangements and policies [4]. A transition from the old method of producing, transporting and using energy has begun and is a major topic in daily political decisions. One of the many supporting elements of the world's energy transition is the integration, adaptation, and exploration of renewable energy resources. Environmentally friendly and supportive ecological technologies such as solar systems, wind turbines, tidal force power plants, biomass plants and biogas facilities are only a few of the many renewable energy technologies (RETs) that humanity is pursuing for the future. In the second half of the 21st century, it is thought that RETs will play a major role in providing energy. Such awareness in both politics and society has led to actions in countries such as Germany, which set a goal of an 80% share of renewables in 2050 [5]; the Netherlands and Norway set incentives to register new cars that do not contain a combustion engine by 2025 [6, 7], and Tesla Inc. pre-sold 400,000 model 3 full electric vehicles in 2016 [8].

One of the most valuable and reliable solutions for renewable energy harvesting is the installation of distributed energy resources (DER), specifically renewable energy power plants. For instance, over the past decade, solar systems have emerged to play a major role in the provision of energy in the future. In Europe, 94,568 MWp of solar power has been installed by the end of 2015 [9]. In the US, 35,800 MWp of solar power has been installed by the end of 2015 [10].

In general, the demand for electricity is time and location dependent. Time dependency refers to the fact that any electrical energy consumed must be produced at the same moment. The correct balance between electric power demand and the production of electricity must constantly be maintained. Imbalances in the electric system lead to extensive network problems and require systems to engage in the balancing of power and energy [11–13]. Because of the history of modern industrialized countries and the development of energy grids, the majority of electric energy in industrialized countries is centrally produced in large, mostly fossil-fuel-based power plants and distributed through widespread electric grids to the end consumer. The origin of this arrangement is that power plants were originally situated at geographical points of interest, e.g., valleys for water power plants, outside of urban areas because of safety issues associated with large coal-fired or nuclear power plants or for colocation with rivers for plants requiring cooling water. A secure electricity grid depends on a constant balance of generation and demand and a well-maintained and constantly functioning electricity grid. In the case of an error in a power line, the underlying grid structure is in danger of congestion and, in the worst case, a blackout [14].

The key challenge for stable and green future energy production, transport, and utilization is the interaction of new technologies. Energy production and consumption are no longer time-coupled. Solar insolation and wind power as energy sources are not always available for consumption because of the seasonal differences, which disturb the equilibrium between energy need and demand in different seasons. Possible solutions to this problem include energy-efficiency projects, demand-side management, energy storage and the transition from electric energy to other physical storage. Electrical energy storage systems (EESs) are seen as a promising technology to solve one part of the overall challenge, the integration of renewable energy producers. One technology currently available (as of 11/2016) to overcome this hurdle is lithium-ion battery (LIB) technology. With the increase in available products in the consumer markets, e.g., smartphones, wearables, and electric vehicles, LIB research has increased significantly over the past decade.

However, LIB research at all levels of expertise, i.e., cell-level, module-level, and system-level research, along with legal, jurisdiction, and economics investigations, must be accelerated further with a focus on market-oriented solutions to make LIB technology available worldwide. This thesis presents LIB technology as a key EES in the near future. Stationary LIB technology, in particular, is considered a major component for a greener future. In the next sub-chapter, a short introduction on the definitions for single-, multi-, and general-purpose technologies is given, and the objectives and hypothesis of this thesis are derived from these definitions.

1.2 Multi-purpose Technology and the "Energy Neighbor" Prototype System

The following material will briefly introduce the idea of a multi-purpose technology, and the basis for this thesis, the outcome of a scientific project [15], namely, the prototype battery energy storage system (BESS) called the "Energy Neighbor."

In general, the literature differentiates technologies according to their general use or a number of applications. So-called single-purpose technologies (SPTs), e.g., a coffee machine, are intended for a single application and serve a single specific need. General-purpose technologies (GPTs), e.g., a personal computer or microprocessor, operate freely and can be used for numerous applications [16] without specific knowledge of the theoretical potential of the technology beforehand. General-purpose technology concepts were first mentioned by Gilles, Williamson and David [17–19], but they were distinctively identified by Bresnahan and Trajtenberg [20] as "[..] *characterized by the potential for pervasive use in a wide range of sectors and by their technological dynamism* [..]" [16] added to the definition, describing GPT "[..] *as a technology that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects* [..]". Describing GPTs and SPTs leads to a definition for multi-purpose technology (MPTs). [21] analyzed several technologies, e.g., lasers and X-rays, fitting the definition of GPT but lacking key indicators [22] clearly identifying them as GPTs. [21] addressed this gap and extended the definition of [23] MPTs as follows:

> *A multi-purpose technology [..] is a technology that has several distinct, economically relevant applications primarily focused on one or a few sectors, yet lacks the technological complementarities of general-purpose technologies. [21]*

Further definitions must include *applications*, which serve as the major identification aspects for MPTs. In the given definition, the applications must be characterized by *specific sources* of economic value and must address a *specific customer group*. In other words, the characteristics of MPTs include different sources of value creation and use by various customer groups. Such technology can be inserted into entirely different value-creating environments and serve completely different customers, value drivers, and competing technologies. In this thesis, BESS devices are defined as MPTs; and neither their full market potential nor the customer value creation potential has previously been estimated (as of 10/2016).

In the following work, a mixture of technology statements describing BESS devices as MPTs, i.e., multi-purpose BESSs (MP-BESSs), descriptions of system design and boundaries, and economic evaluations are presented. Additionally, this work proposes business models for the proposed MP-BESS system architecture and discusses each model with regard to the legal and regulatory framework in Germany as of 10/2016.

Figure 1 – 3D rendering of the Prototype Community BESS, the Energy Neighbor (graphics by Christian Huber).

Under the auspices of the research project EEBatt [15], a prototype MP-BESS called the "Energy Neighbor," [24] (Figure 1) was created at the Technical University of Munich [25] and is currently in use. The author, who acted as the manager of the project during its four-year duration, worked closely with the scientific members to achieve the project's goals. The Energy Neighbor is an MP-BESS based on LIB technology. Its technical data are given in Table 2. This device will serve as a reference system as the MP-BESS technology is discussed throughout this thesis.

After an introduction to SPTs, MPTs, GPTs, and the demonstrator system, the Energy Neighbor, the main issues of this work are summarized, the objectives and goals are given, and the thesis procedure is presented.

1.3 Structure of this Work

Currently, the presence of several technological, legal and economic hurdles impedes large scale installation of BESSs. The main topic and first core issue of this thesis is the *investigation of the technical and legal functionalit*y of LIB BESSs, which originates from the *missing economic value of* LIB BESSs in many cases [26] as of today (10/2016). First, the legal framework conditions, based on the assessment of Germany as a leader in the worldwide energy transition, prevent BESSs from broader implementation and free participation in the existing energy markets in Europe. Non-discriminating and open regulations and frameworks, however, are necessary for a larger rollout of BESSs in grids. Henceforth, the stakeholders and applications for operating a BESS are analyzed and explained. The second core issue is finding a *proper legal framework* for the operation and technical architecture of such systems to increase the economic value. Therefore, BESS devices are defined as MPTs, and a concise framework, i.e., a simulation model and business cases for such systems, is provided. Both of the core issues are examined in detail, and solution suggestions are given for each topic.

The scheme in Figure 2 provides a better understanding of the chapter interconnections and progress clarification.

This thesis, "*Stationary Lithium-Ion Battery Energy Storage Systems: A Multi-Purpose Technology,*" focuses on stationary LIB BESSs and explaining their general structure and function as stationary electricity storage (SES), laying out the possibilities for integration in different voltage grid levels, describing the associated applications and proposing a novel approach for operating LIB BESSs as MPT carriers with the potential for reducing cost and new business models. In Chapter 1, the context of this thesis and a short introduction to the nomenclature critical for understanding the matter are given. In Chapter 2, the basics of BESS technology and specific background information required for this work are explained.

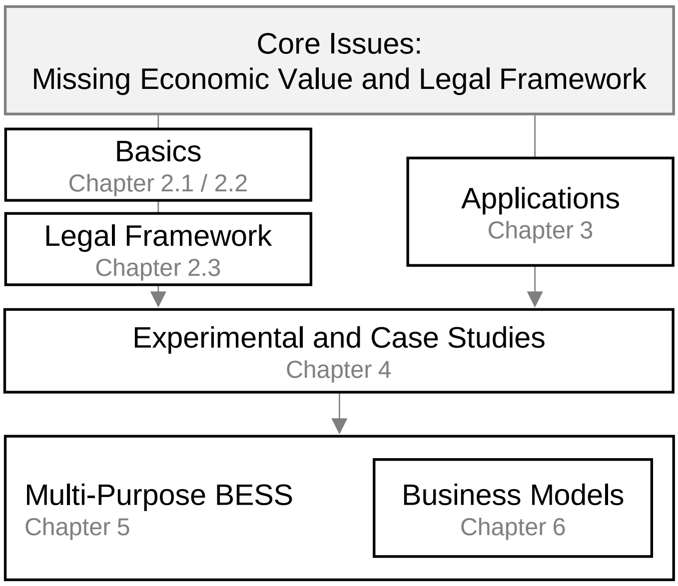

Figure 2 – Quick overview of the fundamental topics, solution approaches, and relating chapters.

Subchapter 2.3 expressly provides a comprehensive view of the legal framework for BESSs in Germany as of 10/2016; relevant parts of this thesis were written under the same circumstances and distinct legal entities. For the general nomenclature in this work, Chapter 3 defines the most common applications for BESSs and lists the subchapters that investigate the applications. The information given is used for a detailed description of MP-BESSs and their functionality. The first core chapter, Chapter 4, presents two excursuses, the results from six case studies that were investigated during the experimental work of this thesis and conclusions regarding the state of BESSs in the context of the core issues of this work. The two following core chapters, Chapters 5 and 6, provide information on the configuration of the simulations performed, key ideas, and theories for the proposed matter and present the business models to legally operate the suggested MP-BESS in Germany. In the concluding Chapter 7, the core issues and results of this thesis are reviewed and summarized, and a comprehensive outlook on energy markets worldwide and in Germany and perspectives on the future for BESSs as MPTs are given.

2 Basics of Stationary Battery Storage Systems

This chapter provides an overview of the technical configuration of a stationary BESS and its related subsystems, states the basic considerations regarding the safe operation of BESSs in stationary applications and explains why this work focuses on LIB technology. Reasons are specifically provided for choosing the LFP/C (lithium iron phosphate) LIB cell chemistry for both the Energy Neighbor and the MP-BESS simulation. When approaching a technology such as LIB BESSs, the specific technical configuration is quite necessary; e.g., the coupling of a BESS, whether it is DC-coupled or AC-coupled, influences the economic value of the BESS because of a change in round-trip efficiencies, operation modes or other considerations. Thus, the fundamental technical arrangement of a BESS is explained, and insights are given on the specifications and their importance for further investigations. The basic concepts of BESS safety, as explained in the following subchapters, are introduced, and the most relevant methods and regulations for safe operation are given as further background information. Additionally, the fundamental legal framework in Germany covering BESSs/SESs, in general, is introduced and the respective stakeholders analyzed. This topic will be revisited in Chapter 6 when business models for MP-BESSs are presented.

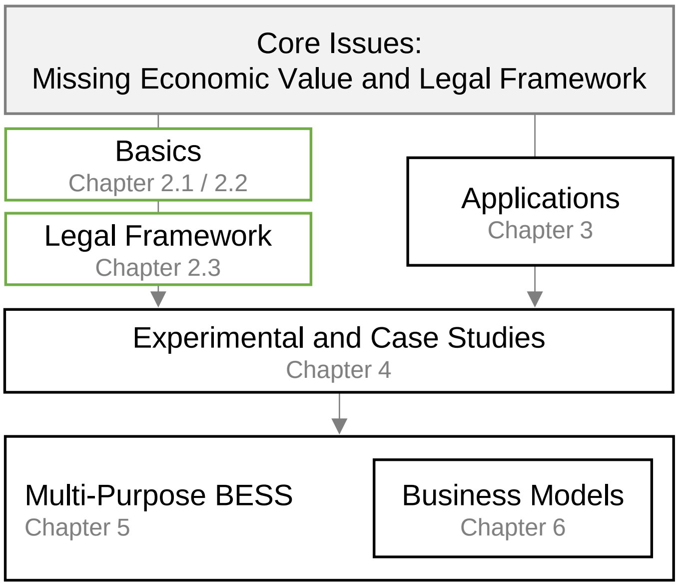

Figure 3 – Progress of work in Chapter 3.

2.1 A General View of Electrical Energy Storage Systems

EESs provide flexibility for decoupling fluctuating energy production and consumption over time and are a key component in the worldwide reduction of carbon emissions. EES technologies have the ability to cope with modern electric grids and are driven by development goals regarding smart infrastructure and smart grids to achieve carbon emission reduction targets. Historically, EESs served customers by reducing electricity costs, improving the reliability of the power supply in critical systems and fostering enhanced power quality, frequency regulation power and voltage quality in grids. In the near future, the role of EESs will shift from these common techniques to new business models, applications and inter-industrial functions, e.g., the coupling of the heat and power sectors. Emerging markets in on-grid or off-grid areas are expected to present major problems in the near future. The quality of life is rapidly improving worldwide, and these advancements are increasing the demand for electricity in all sectors in all countries. EESs are expected to lead to a significant improvement in grid reliability and allow for a second electrification wave around the globe. Modern EES technologies can be used to assist the integration of RETs into existing grids and the implementation of such systems in areas where electric grids do not exist. Many industrial countries have adopted EES technologies to avoid expensive grid construction. The requirement for uninterrupted, elastic power and energy supply and long distances between consumption and generation directly lead to greater EES needs in the future [27].

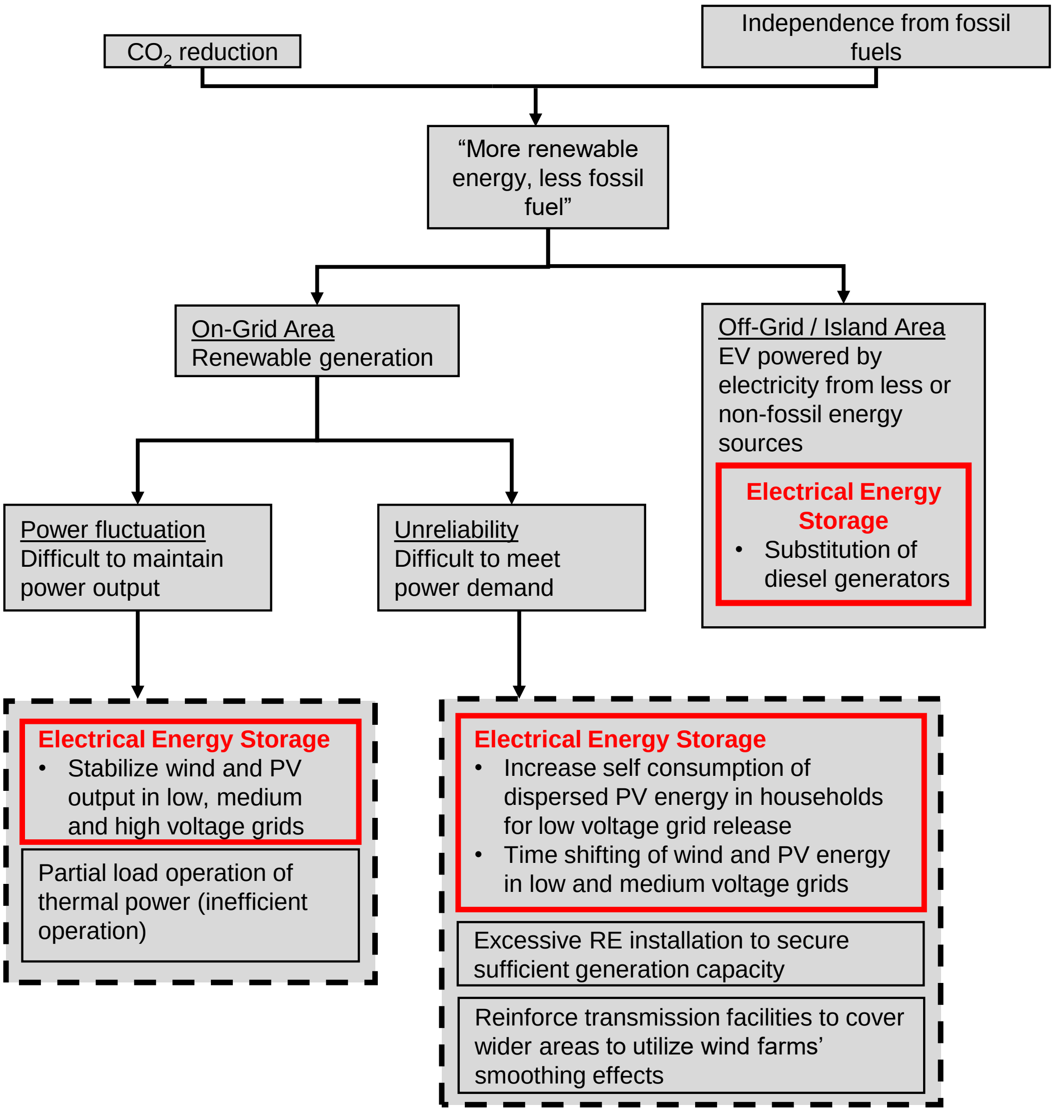

Figure 4 – Problems in DER adoption, specifically CO_2 reduction and the independence from fossil fuels, and possible solutions. Based on [28].

Figure 4 shows the different areas where EESs have been implemented and participate in grid stability and functionality. The specific differentiation between the on-grid and off-grid areas depicts the different approaches EES integration will follow. In on-grid areas, two main factors drive EES integration. First, EESs serve to moderate the output fluctuations of RETs in grids in addition to overtaking the frequency regulation, which is conventionally provided by managing the output of thermal generators to provide control power and allow them to run with a higher efficiency. Second, because RET production is unpredictable and a favorable output time per day is not controllable, RET installations may have overcapacity, which leads to even higher output fluctuations. These fluctuations may be managed in the future by fleets of EESs in new self-regulating markets or by stakeholders who share a common need for constant power output. In off-grid scenarios, the main driver for RET installation is the substitution of diesel generators. For a complete change from fossil fuels to 100% RETs, island structures with strict electromobility concepts and SESs are the most promising technologies.

EESs can provide time shifting, power quality, efficient use of the existing grid, island grids and emergency power. Additionally, electric vehicles and mobile applications are expected to create a reasonably high demand for EESs in the future. The suitability of an EES technology for one of the aforementioned roles, which will be differentiated and explained in more detail in Chapter 3, is determined by the number of cycles and operating time. The number of cycles determines how often an EES must be charged and discharged completely to serve a specific purpose and the operation time defines how often these cycles occur in a given time period. In the following material, each EES technology mentioned in Figure 5 is put into perspective, and their features and a brief description of their functionality and advantages and disadvantages of specific technologies are provided.

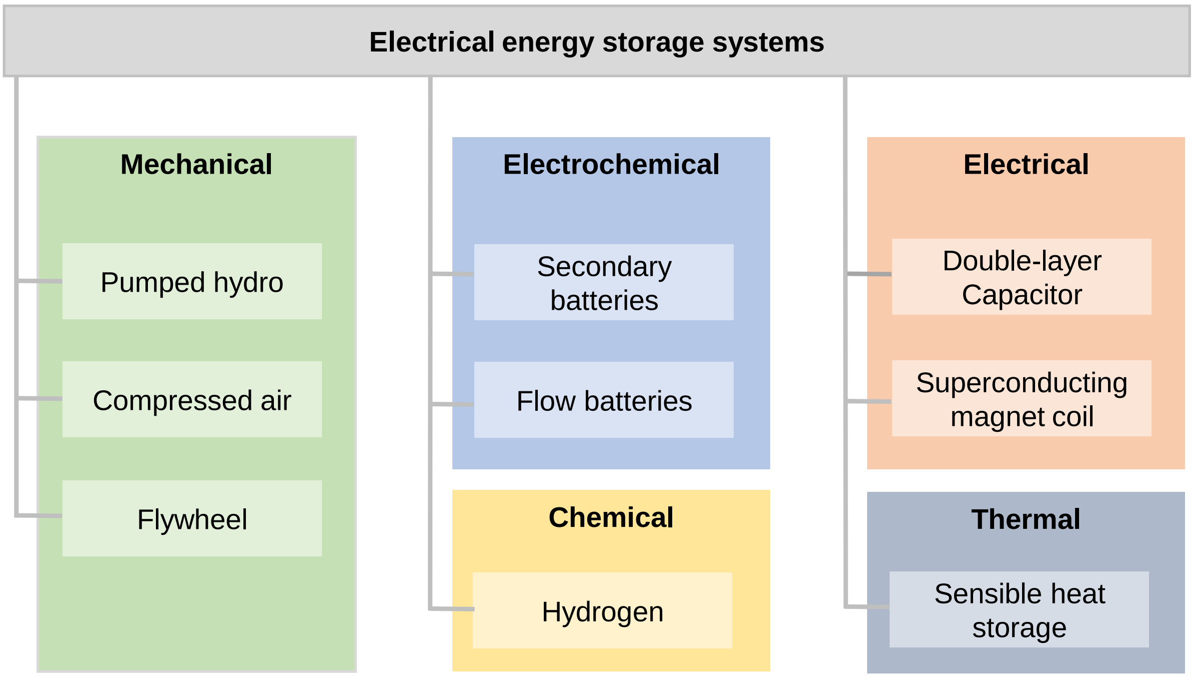

Figure 5 – Classification of EESs. Based on [29].

In general, five different classes of EESs exist, as depicted in Figure 5: mechanical, electrochemical, chemical, electrical and thermal EESs. These EES groups often contain subgroups, e.g., secondary batteries are sub-grouped under electrochemical EESs, which will not be mentioned in the following material because the focus of this work is on LIB BESSs. Other technologies will be briefly described for overview purposes.

Pumped hydro storage (PHS) stores more than four-fifths of the world's renewable electricity [30]. Because of its associated challenges in terms of development, PHS is not commonly used as residential storage. In general, PHS relies on water reservoirs: one upper reservoir (UR) and one lower reservoir (LR). Electricity is stored by pumping water from the LR into the UR and is retrieved by allowing the water to flow back. Modern turbines achieve efficiencies of 70% to 85% [27]. The advantages of this technology are the easy mechanical and technical development, the possible use of local technical knowledge and the high turnaround efficiency[1] [29, 32].

Compressed air energy storage (CAES) stores electricity in the form of compressed air in tanks or caverns under high pressure. Energy is retrieved by allowing the compressed air to flow out of the cavern or tank and decompress while driving a turbine for energy generation. The efficiency of CAES ranges from 40% to 60% depending on the specific setup of a unit. In cases in which the heat of compression is recovered, the efficiency can be as high as 70% [29, 33].

Chemical energy storage in the form of e.g. hydrogen as an energy carrier is an existing technology. Electricity is stored by generating hydrogen via water electrolysis and saving the hydrogen in tanks or caverns. Energy is retrieved by powering any machine that can use hydrogen as a fuel or by directly injecting hydrogen into a fuel cell, where it can react with oxygen to generate electricity and water. A disadvantage of such systems is their efficiency of approximately 32% [34] to 66% [35] for a full energy cycle. [31]

Double-layer capacitors (DLCs) are in general similar to traditional capacitors. DLCs consist of two serial connected interphases electrolyte/electrolyte, resulting in large electrostatic capacity at a limited voltage (below 3V) energy is stored in the form of charge accumulation on both electrode sides [36]. Energy is retrieved by releasing the electric charges from the electrodes through external loads. DLCs provide only small amounts of energy, but they can provide high power peaks for short time periods.

Superconducting magnetic coil energy storage (SMES) stores electric energy in a magnetic field produced by superconducting windings in the magnetic coil. Because SMES requires cryostatic conditions to ensure that the windings are superconducting, large-scale implementation of the technology and experiments has not taken place. [37]

Thermal storage is not explained in detail because of its novelty and mostly one-way function for storing electric energy, i.e., this technology is expected to be used more for sector coupling in the future and differentiated use of electrical energy rather than storage.

During the experimental work for this thesis, the literature and research were used to evaluate the aforementioned EES technologies and determine their typical applications or application modes (APMs). Table 1 provides an overview of APMs in relation to the EESs introduced in Figure 5 and their qualitative ability to serve a specific APM.

The APMs mentioned in Table 1 provide the basis for a better understanding of chapter interconnection and progress clarification.

[1] "*Cycle efficiency, also named the round-trip efficiency, is the ratio of the whole system electricity output to the electricity input.*" [31]

Table 1 – Energy storage systems and their ability to serve a specific APM according to [31, 38] and own research [39] (more stars = higher ability). Abbreviations: CAES – compressed air energy storage; AA-CAES – advanced adiabatic compressed air energy storage; NaS – sodium sulfur; Li-Ion – LIB; DLC – double-layer capacitor; SMES – superconducting magnetic energy storage; H_2 – hydrogen energy storage; FES – flywheel energy storage.

Energy Storage System	El. Chemical				Mechanical				El.		Ch.
APM	Lead-Acid	NaS	Li-Ion	Redox-Flow	Pumped Hydro	FES	CAES	AA-CEAS	DLC	SMES	H_2
Black Start Capacity	**	**	**	**	***	*	***	***	*	*	*
Energy Market Participation	***	***	***	***	**	*	**	**	*	*	*
Grid Quality	**	***	***	**	*	**	***	***	*	*	*
Island Operation	***	***	***	***	*	*	**	**	*	*	*
Peak and Load-Shaving Services	***	***	***	**	***	*	***	***	*	*	*
Primary Control Reserve	***	***	***	**	***	*	***	***	*	*	*
Residential Home Storage	***	*	***	**	*	*	*	*	*	*	*
Secondary Control Reserve	**	***	***	**	***	*	**	***	*	*	*
Tertiary Control Reserve	**	**	***	**	*	**	*	*	*	*	**

BESSs offer a full-range capability over all of the identified APMs in the electric grids. Table 1 provides an overview of EESs and their ability to serve a specific APM. Because of their scalability, high efficiency, long lifetime and fast reaction times [40], lithium BESSs are able to fulfill most requirements for common applications in grids. In addition to lithium BESSs, which is the focus of this work, other technologies have been the subjects of recent research (e.g., redox-flow) [41] or have already been applied to the market (e.g., lead-acid) [42]. This work is focused on LIB technology for multiple reasons.

First, the LIB is the current (11/2016) focus of battery technology research based on an analysis of the DOE database [43] provided by Sandia National Laboratories[2]. Currently, there are 1,628 EES projects, of which 985 involve electrochemical storage and 625 are lithium-ion technology-based.

Second, the market for LIB technology has seen major price reductions [44], and further price reductions for stationary BESS can be expected in the near future too. It is common sense that the price on for stationary BESS will follow the trend vehicle batteries showed. Current BESS prices for a complete system range from 600 €/kWh up to more than 1,200 €/kWh. A self-performed study of worldwide commercially available systems, which was outlined from 01/2016 until 12/2016, identified n = 483 commercially available lithium-ion BESSs in with a mean value of 1,168 €/kWh for storage between 3 kWh and 1.8 MWh. See chapter 4.7 for further details on the study.

[2] The DOE Global Energy Storage Database provides free, up-to-date information on grid-connected energy storage projects and relevant state and federal policies in the U.S.

Third, because of the previously mentioned research focus, a significant amount of scientific work can be expected along with an increase in patents and commercial systems. Research on lithium-ion-cell technologies and the chemistries of the presented systems has increased by more than a factor of 16 from 1990 to 2014 [45]. In addition to their broad capability for serving many APMs with high efficiencies relative to other technologies, lithium-ion systems are a favorable system technology in terms of geographical requirements. Unlike pumped hydro storage systems or compressed air EESs, lithium-ion systems are independent of geographical constraints and easily scalable.

2.2 Technical Framework for BESSs

Subchapter 2.2 explains the structural development of BESS systems and their components. In general, LIB BESS system components consist of the following:

- Battery cells
- Battery management system (BMS)
- Battery cell modules (BMs)
- Energy management system (EMS)
- Power electronics (PE)
- Battery module racks (BRs)
- Containment

On battery management systems

The BMS ensures the safe, reliable and long-lasting operation of the individual battery cells in the BMs and BRs of a BESS. In general, there are three main different types of BMS topologies.

- Centralized BMS
- Decentralized BMS
- Master/slave BMS

In most cases, master/slave topologies are applied in BESSs because of their favorable safety features, the possibility for redundant design and cost-effectiveness compared to centralized and decentralized BMS [46]. The fundamental task of the BMS is to secure individual serial cell blocks of BMs so that at any operation time they are in a safe operation area (SOA). SOAs are mostly defined by the technical parameters of a single LIB cell and are defined by the maximum/minimum temperature, maximum/minimum cell voltages, and maximum/minimum cell currents. The slave BMS (SBMS) monitors each individual cell parameter to assist the master BMS (MBMS) in determining state variables. The state variables mirror the current technical state of a BESS. Commonly used state variables include the state of charge (SOC) [40], which reflects the amount of energy that has been charged into an LIB cell relative to its maximum energy capacity, and the state of health (SOH) [40], which reflects a cell’s aging through the increase in the LIB cell inner resistance and the capacity fade after time in operation relative to an LIB cell’s initial capacity and inner resistance. Recently, other state variables, e.g., the state of safety (SOS) [47] or state of function (SOF) [48] have been introduced, but they will not be addressed further in this thesis. A second core feature of the SBMS is the coordinated discharge of single serial cell blocks in a BM to balance the differences between cell blocks due to manufacturing inaccuracies or temperature imbalances inside a BM, which can both lead to different chargeable capacities per charge/discharge cycle. The BMS communicates mainly via the BUS system, but there are new developments toward wireless BMSs [49]. Typically, SBMSs are measuring devices, and a MBMS consists of appropriate controlling interfaces, e.g., high-voltage relays or insulation monitors, logging and communication infrastructure. Beside subunit redundancy, MBMS functionality is implemented by doubling software-code and hardware structures to achieve reliability on a single MBMS.

On battery modules

When LIB cells are interconnected to modules, different types of serial and/or parallel connections lead to BMs. A BM provides usability, safety, and reliability to the BESS. Other reasons for packaging LIB cells into BMs are restrictions on the maximum DC voltage in a single system, i.e., < 60 VDC low-voltage (LV) systems or maximum weight for handling purposes. Figure 6 depicts a module of the Energy Neighbor system, which was introduced in Subchapter 1.2. This specific module is comprised of 192 cells with a total capacity of 1.84 kWh. The full technical data for this module and the Energy Neighbor are provided in Table 2.

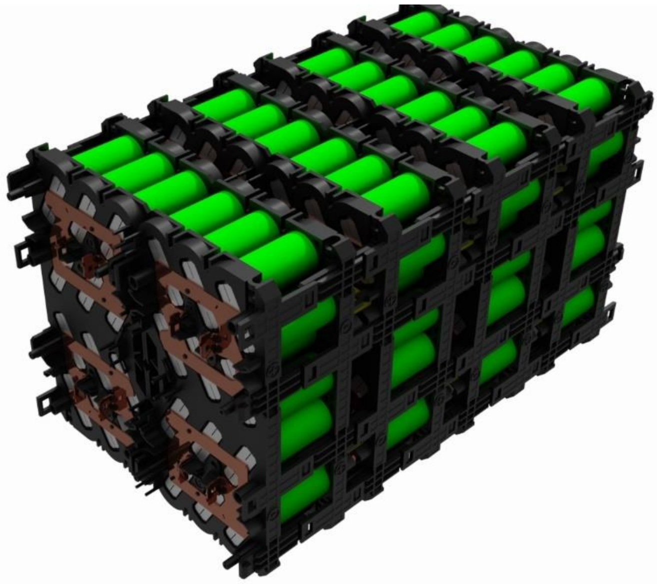

Figure 6 – An Energy Neighbor battery module composed of 192 SONY LFP/C 26650 cells providing 1.84 kWh of energy. (Rendering by Christian Huber).

On energy management systems

EMSs are active and self-operating systems within a BESS, and they appear in several layers of BESSs. Mainly, EMSs coordinate energy and power flows in BESSs [50, 51] by incorporating all the necessary information, e.g., SOC, SOH, external loads, and BESS temperature, and directing it along with an operational strategy (OS) for the overall power flow of a BESS. EMSs can be built in a variety of topologies, similar to BMSs. However, a top-layered active EMS with EMS subunits is currently the most common EMS in BESSs. A top EMS controls the overall

BESS power flow constantly through communication with sub-EMS systems to coordinate the internal state variables, which are derived from the MBMS, measured by the SMBS.

On power electronics and BESS efficiencies

PE for LIB BESS are of interest because of efficiency problems. A LIB cell, specifically the cell used in this work, an LFP/C cell, reaches different voltages during charging and discharging. For instance, a SONY26650FTC cell ranges from 2.0 V in cut-off voltage to 3.6 V maximum charging voltage. Thus, a module composed of the aforementioned 192 LIB cells arranged in a 16s12p order will show a cut-off voltage of 32 V and a charging end voltage of 57.6 V. Furthermore, the Energy Neighbor's battery module racks consist of 13 modules, which results in a cut-off voltage of 416 V and a charging end voltage of 748.8 V. The full technical data are available in Table 2.

$$U_{stack,max} = U_{cell,max} * n_{cells,module} * n_{module.rack}$$
$$U_{stack,max} = 3.6\,V * 16 * 13 = 748.8\,V \tag{1}$$

$$U_{stack,min} = U_{cell,min} * n_{cells,module} * n_{module.rack}$$
$$U_{stack,min} = 2.0\,V * 16 * 13 = 416\,V \tag{2}$$

Thus, a power electronic component for a LIB BESS must be able to accommodate intermediate circuit voltages of 420 V to 750 V with adequate efficiency under a partial load. Figure 7 depicts the trade-off between a PE unit that operates (e.g., on small loads) with high efficiencies but lacks DC link voltage support for low voltage levels.

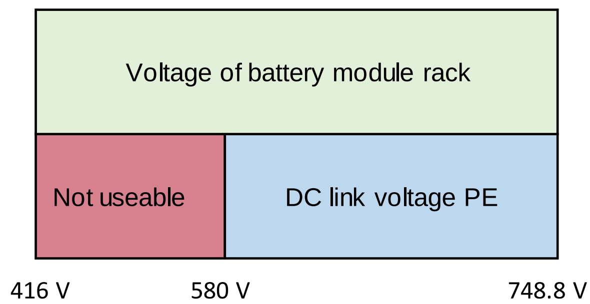

Figure 7 – Possible operating voltage areas for the PE and LIB module racks of the Energy Neighbor.

The efficiency of a BESS may be given by

$$\eta_{BESS} = \eta_{PE} * \eta_{LIB} * \eta_{SYS} \tag{3}$$

where η_{PE} represents the efficiency of the power electronics, e.g. losses in the IGBTs, η_{LIB} representing the LIB's efficiency and η_{SYS} the system's architectural losses, i.e. stand-by power losses or climate system losses. The LIB round-trip efficiency is described as

$$\eta_{LIB} = \frac{\int_0^t P_{LIB_{discharge}}(t) * dt}{\int_0^t P_{LIB_{charge}}(t) * dt} * 100 \tag{4}$$

the ratio between the discharged energy $P_{LIB_{discharge}}$ over a period t and the charged energy $P_{LIB_{charge}}$ over a period t or a specific number of equivalent full-cycles and the condition that the initial and final state of charge are identical; thereby P_{LIB} reflects the DC power on the connection of the batteries. Any LIB internal units, e.g. a BMS or EMS component, may lower this ratio. The PE's efficiency is given by

$$\eta_{PE_{charge}} = \frac{\int_0^t P_{LIB_{charge}}(t)dt}{\int_0^t P_{BESS_{charge}}(t)dt} \text{ and } \eta_{PE_{discharge}} = \frac{\int_0^t P_{BESS_{discharge}}(t)dt}{\int_0^t P_{LIB_{discharge}}(t)dt} \tag{5}$$

as the ratio between total energy charged into the LIB $P_{LIB_{charge}}$ and the total energy consumed by the BESS $P_{BESS_{charge}}$ over a period t; equal for discharge scenario; thereby $P_{BESS_{charge}}$ reflects the AC power on the connection of the batteries PE units. Hence, the round-trip efficiency of a PE unit in a BESS follows

$$\eta_{PE} = \eta_{PE_{charge}} * \eta_{PE_{discharge}} \tag{6}$$

Similar the BESS efficiency η_{SYS} is given by additional consumers in the BESS; these may not be a part of either the LIB, accordingly, embodied BMS and EMS systems, or the PE units. Hence, η_{SYS} describes stand-by losses, losses for automated climate control inside the system, losses for safety equipment as well as servers or other communication technology

$$\eta_{SYS_{charge}} = \frac{\int_0^t P_{BESS_{charge}}(t)dt}{\int_0^t P_{GRID_{charge}}(t)dt} \text{ and } \eta_{SYS_{discharge}} = \frac{\int_0^t P_{GRID_{discharge}}(t)dt}{\int_0^t P_{BESS_{discharge}}(t)dt}$$
$$\eta_{SYS} = \eta_{SYS_{charge}} * \eta_{SYS_{discharge}} \tag{7}$$

thereby $P_{GRID_{charge}}$ reflects the AC power on the connection of the whole BESS to the grid. Typical data are as follows

$$\eta_{BESS} = 96\% * 98\% * 90\% = 84{,}67\% \tag{8}$$

Hence, the overall two-way efficiency of an exemplary LIB BESS is about 85%. PE units are important components of LIB BESSs in regards to the overall system efficiency and their general configuration, as well as other power consuming system components. The existing differences between the battery and DC link voltage of PE units must be included when choosing a LIB cell, designing modules and assigning system voltage levels. In Subchapter 5.5, a possibility to increase the overall efficiency when dealing with an MP-BESS is presented.

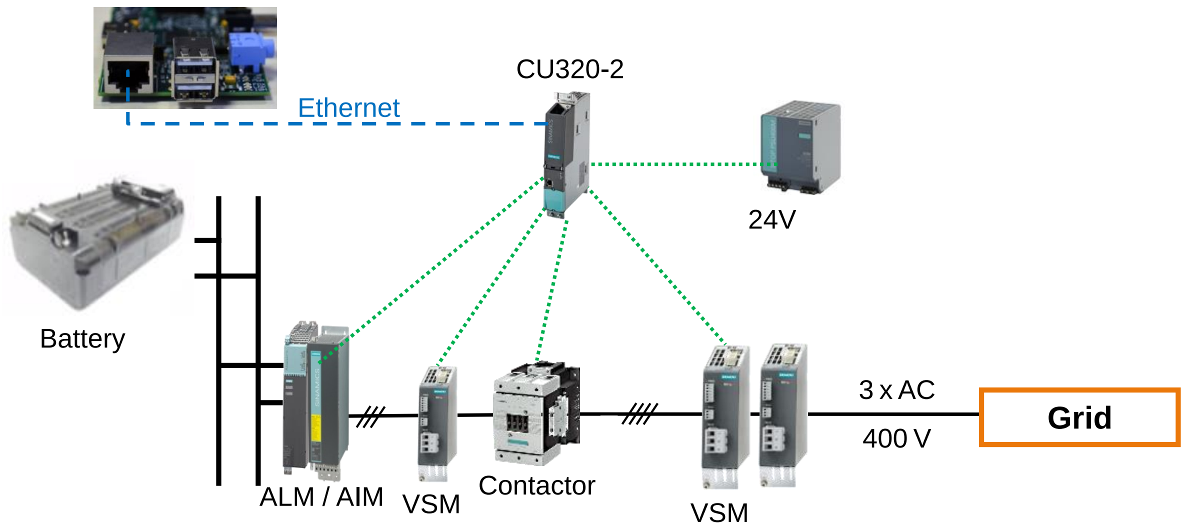

Figure 8 – Schematic of a single BM connected via PE setup to the grid with all necessary subcomponents

Providing a better understanding, Figure 8 depicts an exemplary setup of a PE for the Energy Neighbor BESS. The complete PE is comprised of an active line module (ALM), an active interface module (AIM), a voltage-sensing module (VSM) and a control unit (CU); though shown specifically for the Energy Neighbor, any BESS will embody similar units[3]. Herein the ALM generates a controlled inter-circuit DC voltage and connects the battery to the grid. The AIM contains filters and line chokes for voltage and phase adaption to the grid. Voltage signals, measured by the VSMs, are sent directly to the CU, which communicated directly to the EMS, contactors, and switches.

The PE is a direct communication and translation part between the grid and battery source for both charging and discharging the BESS, hence efficiency, possible DC voltage ranges and overall functionality of PE units cover an important role in BESSs.

Figure 9 – An Energy Neighbor battery module rack comprised of 13 modules. (Rendering by Christian Huber)

On battery module racks

Similar to battery modules, BRs combine several battery modules into a single unit. BRs can be designed in several ways, and the most interesting point is the handling of a series of BRs and each BR's internal electrical configuration.

The Energy Neighbor, for instance, is composed of 13 modules per BR, as depicted in Figure 9, each connected in series to the next module, which results in the cut-off and open-circuit voltages presented in Table 2. Other LIB BESSs, which do not need high DC voltages for powerful PE units, may be composed of BRs connected in parallel or in a mix of series and parallel. Most large LIB BESSs will contain several BRs. These, in most cases, will be connected via a DC link to a single, large, centralized PE unit. In this thesis, however, a single BR is connected to an independent, smaller, PE unit; refer to Figure 50, the MP-BESS schematic. By joining PE units with single BR units, further improvements in efficiency can be achieved and will be outlined in this work, specifically in Subchapter 5.5.

[3] The depicted units are manufactured by Siemens under the name Sinamics S120.

Table 2 – Energy Neighbor Prototype BESS technical data.

	Name	Value	Unit
System	Nominal energy	191.36	kWh
	Maximum power	248	kW
	Grid connection	400	VAC
	Power electronics		
	6x	36	kW
	2x	16	kW
	racks	8	pc
	Nominal capacity	288	Ah
Rack	Modules per rack	13	pc
	Nominal voltage	665.6	V
	Cut-off voltage	416	V
	Max. charging voltage	748.8	V
	Nominal capacity	36	kAh
	Nominal energy	23.96	kWh
Module	Cells per module	192	pc
	Configuration	16s12p	
	Nominal voltage	51.2	V
	Cut-off voltage	32	V
	Max. charging voltage	56	V
	Nominal capacity	36	Ah
	Nominal energy	1.84	kWh
Cell	Manufacturer	Sony	
	Cell technology	LFP/C	
	Cell size	26650	
	Nominal voltage	3.2	V
	Cut-off voltage	2.0	V
	Max. charging voltage	3.6	V
	Max constant discharge current	20	A
	Nominal capacity	3.0	Ah
	Nominal energy	9.6	Wh

2.2.1 Lithium-Ion Cell Types

This subchapter covers common LIB chemistry configurations with a focus on the most favorable chemistries for stationary BESSs. Their key characteristics will be briefly compared. Further, the reason that the LFP/C LIB technology is a promising candidate for LIB BESSs will be addressed.

One of the most promising technologies (as of 08/2016) for SES is LIB technology. LIB or secondary cells are favored by many users because of their high efficiencies of 95% and up to 99% [40] and relatively long lifetimes of up to several thousand cycles [52] for electrochemical systems. In general, three basic LIB configurations are used: lithium metal batteries, LIB and lithium polymer batteries [53]. In general, lithium metal batteries benefit from a pure lithium metal electrode, which donates lithium ions for internal reaction processes; these batteries offer better energy-to-weight but lack better power-to-weight ratios due to limitations in maximum charging currents. However, a pure lithium metal electrode leads to unstable operation conditions because of the charging and discharging behavior; during discharging, the lithium metal is dissolved from the negative electrode and forced back onto the negative electrode during charging. Due to an internal non-controllable process, the lithium metal deposits back onto the negative electrode in diffuse shapes, which can lead to dendritic growth and penetration of the intercellular safety barriers, i.e., the separator [53–56]. Therefore, LIBs were developed as lithium intercalation electrodes to prevent the specific plating behavior as much as possible and to stabilize the charging and discharging processes.

The first LIB systems were introduced by Sony in 1991 ($LiCoO_2$, LCO) in camcorders and by Nokia in their mobile phones [57]. Intercalation electrodes prevent the harsh lithium metal reactions through the absence of pure lithium metal during the charging and discharging phases. Carbon compounds and lithium metal oxides are mostly used for intercalation electrodes as the negative and positive electrode, respectively.

The LIB systems specifically mentioned above can be constructed with varying intercalating electrode materials for the positive and negative electrodes. Advances in technology and research have resulted in a broad variety of chemistries available to markets for LIB, and the configurations all provide positive and negative abilities for each application. In general, most positive electrode materials form one of three structures:

- *Olivine lattice* (e.g. $LiFePO_4$) provides one-dimensional linear Li^+ movement, high safety, high cycle life, moderate cost, low voltage for $LiFePO_4$
- *Layered structures* (e.g. $LiCoO_2$) provide two-dimensional Li^+ movement, high specific capacity, moderate security, and high costs
- *Spinel lattice* (e.g. $LiMn_2O_4$) provides three-dimensional Li^+ movement, high specific power, moderate cost, and moderate stability

Commonly used anode materials are as follows:

- Graphite
- Hard carbon
- $Li_4Ti_5O_{12}$ (lithium titanate)

Each of the aforementioned cathode and anode materials has advantages and disadvantages in regard to BESSs, and these are shown in Table 3. The evaluations (more stars = better performance) were gathered from a literature review, expert knowledge, and research.

Table 3 – Common LIB chemistries and their overall ratings among the most important properties: safety, power density, energy density, cell costs without system technology and lifetime expectations. Based on [58, 59].

Chemistry (Cathode/Anode)	LFP/LTO	NMC/C	LFP/C	LMO/C	NCA/C
Safety	****	***	****	***	**
Power Density	***	***	***	***	****
Energy Density	**	****	**	***	****
Cell Costs	*	***	***	***	**
Lifetime	****	***	****	**	****

There are no single criteria that promote a specific cathode-to-anode configuration over another for specific use cases; however, certain advantageous characteristics serve specific APMs better than others. For example, the most commonly deployed LIB cell technologies in electric vehicles are NCA/C and NMC/C because of their high energy and power density, which are necessary to operate such systems, and the lower safety performance or possible lifetime is an accepted limitation. The characteristics favorable for BESSs are cycle stability, system safety and low costs. Other less important characteristics are represented by weight and volume because most stationary BESSs are not constrained by a limited space. However, the race for better LIB cell technology will accelerate because future stationary BESSs are expected to be distributed in metropolitan regions or cities that suffer space problems.

On LFP- $LiFePO_4$ (Lithium Iron Phosphate)

The LFP battery technology is mostly known for its cycle stability, low internal resistance, and physical robustness. Since the first scientific articles in 1997 [60] and commercialization, this technology has gained attention for BESS applications and as a replacement for starter batteries in cars. The specific combination of materials forms stable phosphor-olivine structures that offer relatively low internal resistance and allow the systems to provide relatively high discharge rates of up to 25 C at a moderate voltage of ~ 3.5 V [61].

In addition, the LFP chemistry is more tolerant to high charge potentials. Because of the lack of an exothermal reaction of Lithium Iron Phosphate at high temperatures, LFP LIB cells have excellent safety properties. Moreover, LFP LIB cells offer low cost, long cycle life, and chemical stability, which makes them particularly suitable for BESSs.

On NMC-$LiNiMnCoO_2$ (Lithium Nickel Manganese Cobalt Oxide).

The NMC LIB technology is one of the most prominent technologies used for certain applications in the mass market. The combination of nickel and manganese eliminates to a certain extent the disadvantages of each material. While nickel provides a relatively high specific energy, it has poor stability. Manganese forms spinel structures with high stability and loading abilities that result in low internal resistance at relatively low specific energies. The mix of materials is most commonly a ratio of 1-1-1, representing equal thirds of $Ni_{1/3}Ma_{1/3}Co_{1/3}$ in the cathode. NMC is mostly used in all-electric vehicles, electric bikes, and power tools [62].

On NCA-$LiNiCoAlO_2$ (Lithium Nickel Cobalt Aluminum Oxide).

The NCA LIB technology is a development of the lithium nickel oxide (LNO) technology. The substitution of cobalt for nickel and further stabilization of the lattice with aluminum makes NCA sufficiently stable for commercial application with up to several thousand cycles at high currents [53]. NCA is mainly used in cells in which the key criteria are a high specific energy and long lifetime. The diminished safety of these cathodes can be partly compensated by suitable battery management systems and cell design. NCA is mostly used in cars or mobile devices.

On LTO- $Li_4Ti_5O_{12}$ (Lithium Titanate).

The LTO LIB represents a different approach to cell design. Li-titanate replaces the graphite anode in typical LIB chemistry, but the cathode is LFP, NCA or NMC. With a relatively low nominal cell voltage of ~ 2.4 V, the LTO chemistry lacks a high specific energy but is able to charge and discharge at relatively high rates [53]. The technology also provides long cycle lifetimes and excellent safety behavior. LTO LIB are typically operated in electric powertrains or solar-powered street lighting [63].

On the SONY LFP 26650 cell.

As mentioned above the LFP LIB technology promises to provide great benefits over other technologies for the case of LIB BESS. In several experiments, performed by the project partner VARTA, the EEBatt Project concluded, that the Sony US26650FTC1 is an ideal cell for LIB BESS in stationary applications. The chosen cell combines high safety features and behavior, reasonable pricing and extended calendric and cyclic lifetime expectations. The following shows data from calendar aging, cycle aging, nail penetration and overcharge experiments of the Sony US26650FTC1 performed by members of the EEBatt research project.

Among the most commonly used LIB technologies, lithium iron phosphate ($LiFePO_4$ or LFP) chemistry is favorable for use in stationary BESSs, as it combines a long lifetime with high cycle stability and high safety standards with moderate costs. Adding, due to its comparably low voltage at even high SOCs LFP LIB cells do not operate in aging critical conditions. Thus, this work, as well as the setup of the Energy Neighbor prototype, focuses on the LFP technology for simulation and lifetime estimation, except in Subchapter 5.4, in which a NMC technology is investigated.

Figure 10 depicts the results of the calendric aging tests with the Sony US26650FTC1. For each test point, five cells were selected. With three test scenarios a) – c)[4] at each test point the cells were continuously measured every 30 days by performing a full discharge and charge regime. According to the data, high SOC levels, as well as high cell temperatures, lead to faster degradation, which aligns with the literature [64]. With a total loss of 75 mAh capacity the five test cells at 45 °C 0 % SOC showed the best calendric aging behavior, i.e. least capacity loss. Given that the Energy Neighbor system will be equipped with a sophisticated cooling system, 45 °C reflects a realistic cell environment. Hence, the Sony US26650FTC1 is a promising fit for LIB BESS.

[4] a) storing at 60 °C 100 % SOC; b) storing at 60 °C 0 % SOC; c) storing at 45 °C at 0 % SOC

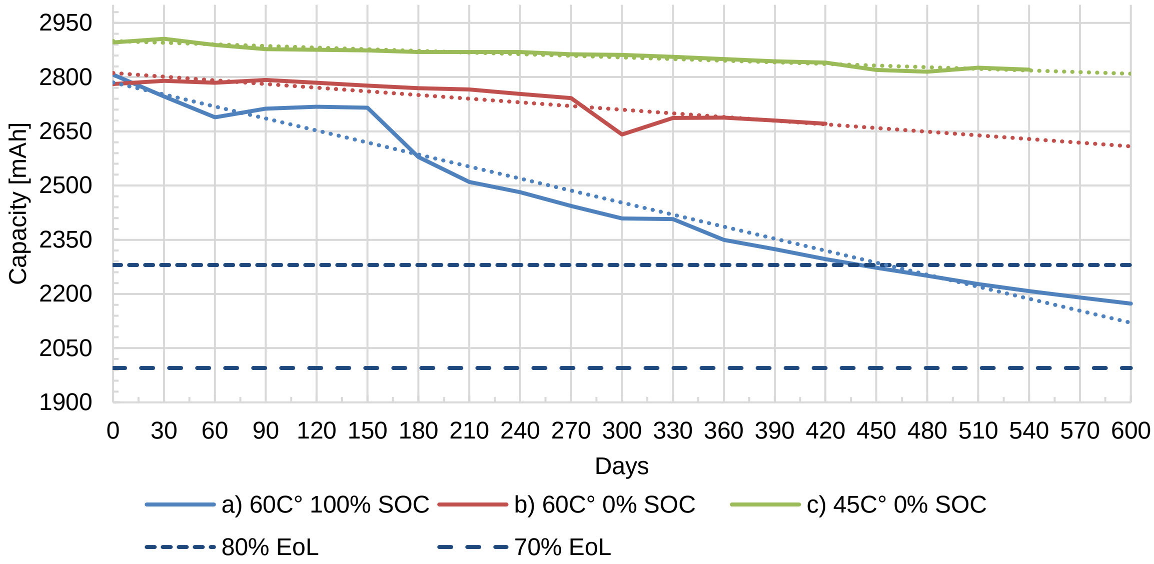

Figure 10 – Capacity fade of Sony 26650 LFP/C LIB cells under laboratory conditions derived from quintuple measurement points by calendric aging experiments with test regimes (in the legend) and accordingly 80% and 70% EOL marks.

Figure 11 depicts the resulting data from cyclic aging experiments with the Sony US26650FTC1. Five cell pairs, similar to the calendric aging experiments, were tested under four different regimes a) – d). The data shows that the cell shows good aging behavior and loses capacity in a mostly steady and non-accelerated trajectory.

Table 4 – Parameter of the cyclic aging experiments with the Sony US26650FTC1 at 25 °C

Test	charging	discharging
a)	charge current: 0,9 A (≙ 0,3 C) max. charging voltage: 3,45 V cut-off current: 100 mA	discharge current: 0,9 A (≙ 0,3 C) cut-off voltage: 2,6 V
b)	charge current: 2,7 A (≙ 0,9 C) max. charging voltage: 3,6 V cut-off current: 27 mA	discharge current: 2,7 A (≙ 0,9 C) cut-off voltage: 2,0 V
c)	charge current: 3,0 A (≙ 1,0 C) max. charging voltage: 3,45 V cut-off current: 100 mA	discharge current: 3,0 A (≙ 1,0 C) cut-off voltage: 2,6 V
d)	charge current: 3,0 A (≙ 1,0 C) max. charging voltage: 3,6 V	discharge current: 3,0 A (≙ 1,0 C) cut-off voltage: 2,6 V

Especially experiment a) was of high interest, because it reflects the necessary safety voltages which the BMS and EMS will maintain the cells in while the BESS will be fully operational. During testing the capacity has consistently been measured as the discharging capacity according to each test regime a) to d). With almost 15.000 cycles, the aging behavior does not show any jumps or impulsive behavior, promising the Sony US26650FTC1to be a fit for the Energy Neighbor BESS.

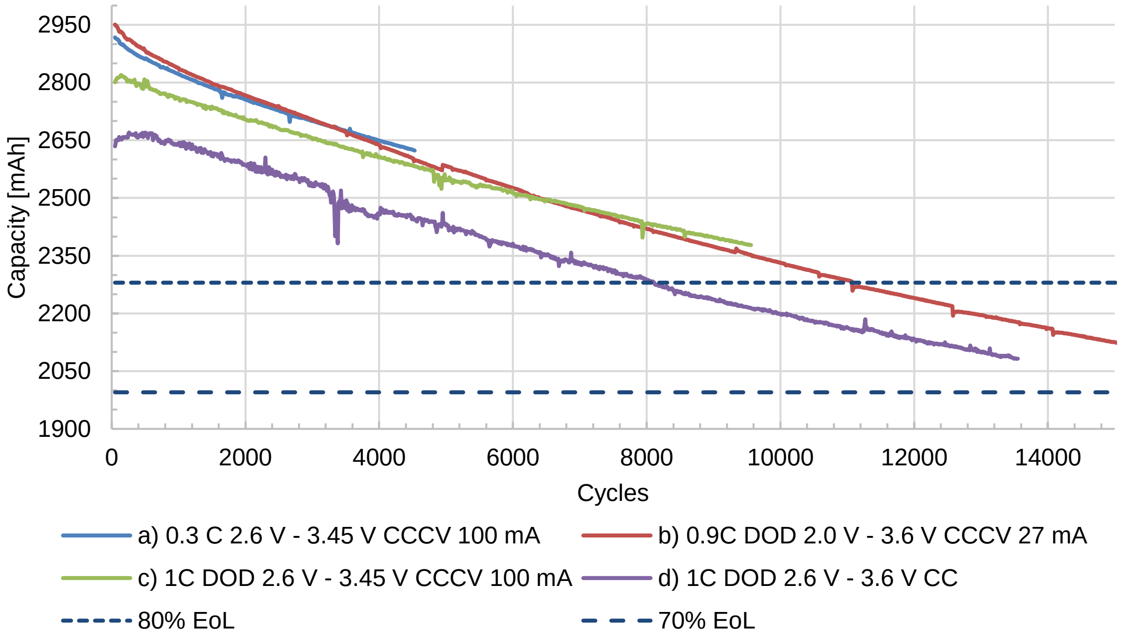

Figure 11 – Capacity fade of Sony 26650 LFP/C LIB cells under laboratory conditions derived from quintuple measurement points by cycle aging experiments with states regimes (in the legend) and accordingly 80% and 70% EOL marks. Peaks in test data occurred due to the necessity to restart the experiments after each 500 cycles.

Besides performance tests, the safety behavior of a LIB is a crucial factor for choosing a cell for BESS. Figure 12 shows the experimental data for a nail penetration test according to the UN 38.3 test regime.

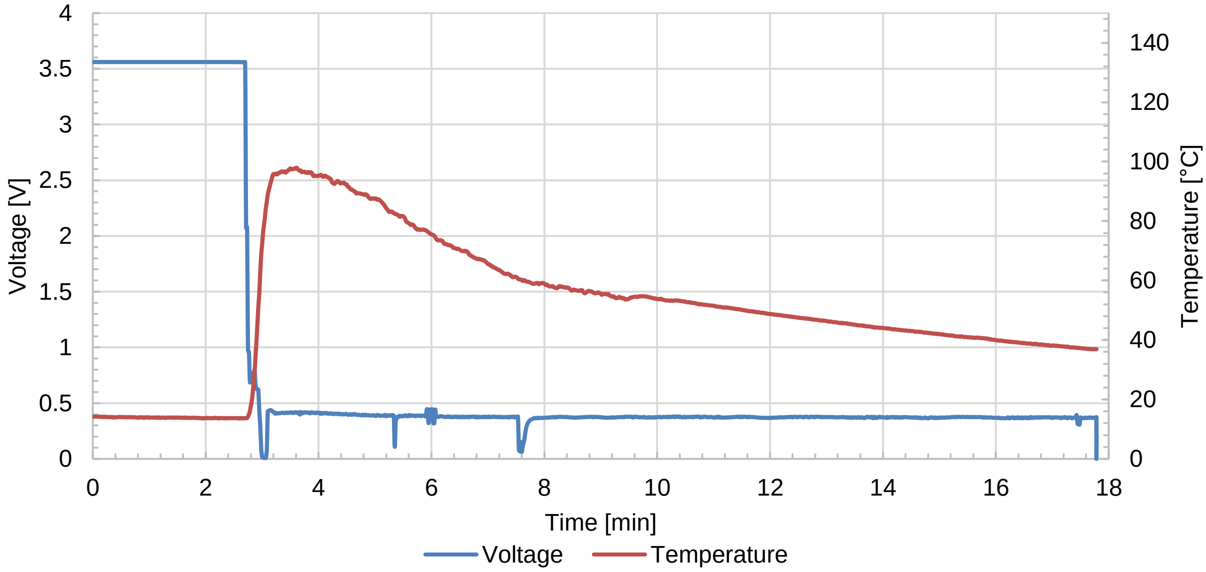

Figure 12 – Nail penetration test with resulting cell temperature and voltage after nail penetration at 2:45 minutes in the experiment of the Sony LFP 26650 cell at 100% SOC.

The cell was penetrated with a 4.2 mm diameter nail and a feeding speed of 3 mm/s. After heating up to 100 °C, the cell released some liquid electrolyte in the area of penetration with small bubbles under the emission of small gas threads. No flames were observed. Hence, the cell fulfills the EUCAR Hazard level 4 criteria according to nail testing [65].

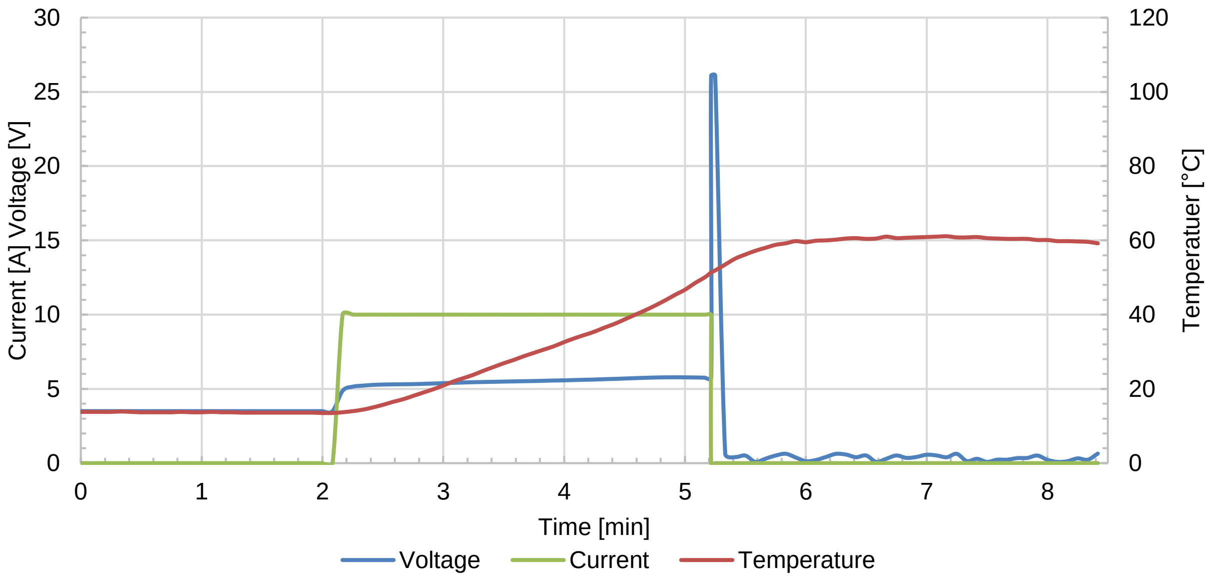

Figure 13 – Overcharge test with resulting cell temperature, current and voltage after applying an overcharge current of 10A at ~ 2 minutes in the experiment to the Sony LFP 26650 cell.

Another safety test underlying the Sony US26650FTC1 cell's suitability for application in a LIB BESS is an overcharge test. Figure 13 shows the resulting data from an overcharge test with 10 A. At this moment the cell is overcharged with a constant current and no voltage restriction. At roughly 3 minutes in the test, the CID spontaneously cracks, and gas is released. The cells neither catch fire nor burst or explode; reaches a maximum temperature of about 60 °C. Hence, the cell fulfills the EUCAR Hazard level 4 criteria according to overcharge testing [65].

By providing exemplary data from a both performance and safety tests, it has been shown that the Sony US26650FTC1 is a favorable cell for implementation in stationary LIB BESS, specifically the Energy Neighbor demonstrator system built by the Technical University of Munich.

It is important to mention that other cell systems may offer similar or better overall ratings for a possible adoption due to e.g. higher energy or mitigated safety issues on module level or system level. However, for the sake of usability and especially handling of a large amount of cells in an experimental environment, LFP chemistry seemed favorable.

2.2.2 System Safety

The following subchapter provides a short overview of relevant safety systems and regulations for operating a stationary BESS under the German standards. With the decreasing cost of LIB BESSs, these systems have become increasingly more attractive to a broader range of APMs, which will be outlined in detail in Chapter 2.3. Currently available BESSs range from several kWh up to several MWh of capacity. One of the largest projects in Germany will be commissioned by STEAG AG and will be comprised of 4 BESSs rated at 90 MWh. A large number of similar pilot projects worldwide emphasize the necessity for minimized risks. Currently (as of 08/2016), long-term studies are lacking on the safety of such systems operated under real conditions. To ensure system security and safety, it is essential to be aware of relevant legislative and normative requirements as well as safety operating technologies and subsystems in BESSs. Currently, there are no standards for the safe constructions, commission, operation, decommission and recycling of stationary BESS; however, a series of norming institutes are working closely with industry and policy makers to fill this gap.

Legislative regulations in the European Union require any technical system that is being sold into public markets to comply with all conformity regulations according to the CE mark. Under the CE mark, the following regulations are relevant for stationary BESSs:

Machine Guideline (2006/42/EG)

Even if stationary BESSs are not a machine in the sense of 2006/42/EG, the failure of safety systems inside a BESS can lead to significant dangers for persons working with these systems. The demand of 2006/42/EG requiring "*a component which serves to fulfill a safety function or the failure and/or malfunction of the safety of persons at risk*" should be ensured in a stationary BESS.

EMC Guideline (2004/108/EG)

To ensure the correct operation of a stationary BESS, the electromagnetic compatibility guidelines cover any issues relating to disturbances between components of a BESS from both external and internal sources as well as emitting disturbance to the outside of the BESS. Specifically, PE, communication busses, EMSs and BMSs require audits by recognized and certified institutes.

LV Guideline (2006/95/EG)

The LV guideline 2006/95/EG is mandatory for any electric system connected to AC between 50 VAC and 1,000 VAC. Because many BESSs are in this range, this guideline should be applied. The guideline "*ensures that electrical equipment may be placed on the market only if they are prepared so, that they ensure, under a proper installation and maintenance as well as an intended use, the safety of people and animals, and - according to the given community - status of safety technology and do not jeopardize the preservation of material assets."* [66].

RoHS-Guideline (2011/65/EU)

The guideline for the *Restriction of (the use of certain) Hazardous Substances* represents an important guideline to protect animals, humans, and the environment from dangerous materials. It is mandatory in the European Union that all systems follow this guideline; thus, a BESS is equally affected.

Product Safety Directive (2001/95/EG)

The product safety directive ensures that technical systems that are sold on the market are only allowed to be sold when they do not risk the safety of persons and assets. It is mandatory in the European Union that any system follows this guideline; thus, a BESS is equally affected.

ErP/Eco-Design-Directive (2009/125/EG)

The eco-design-directive is especially pertinent for BESSs. The directive "*contributes to sustainable development of technical systems by increasing energy efficiency and the level of environmental protection and at the same time improving the security of energy supply*." A BESS is affected by this directive.

R&TTE-Directive (1999/5/EG)

Each of the aforementioned guidelines or directives focuses on different safety issues. Not all of these apply in every country. However, the safety of such systems has a high impact on market success, and the highest standards and safety state should be reached for stationary BESSs.

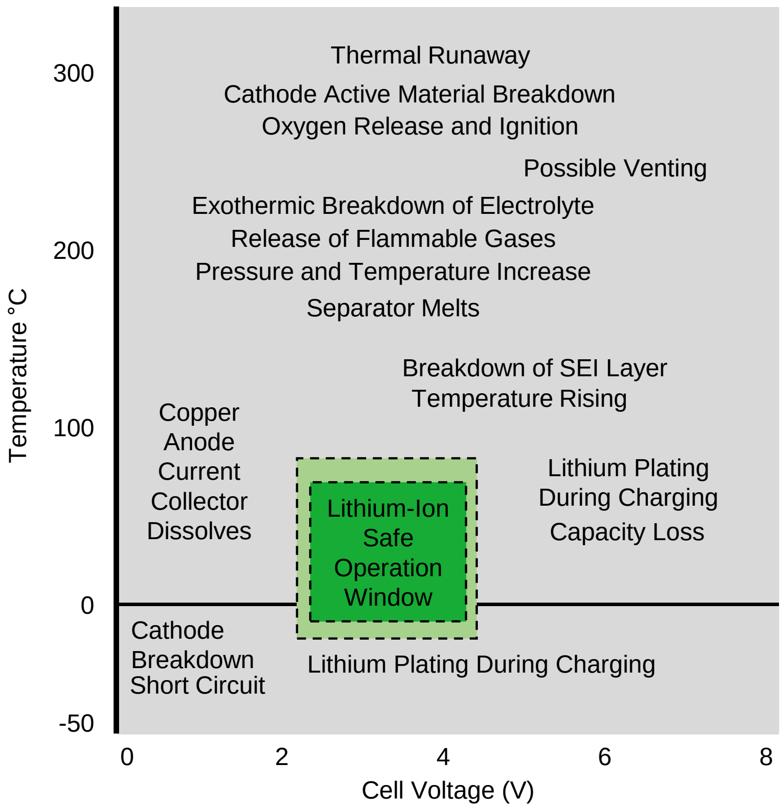

Figure 14 – LIB cell safe operating window. Based on [48][5].

Figure 14 depicts a general overview of the safe operation window for LIB cells, e.g., over-voltage and under-voltage, overcharge and over-discharge, or high temperature and low temperature. However, the safe operation window of LIB cells varies between cell types, and each cell must be treated differently according to the aforementioned boundaries.

The requirement to monitor each cell is a major challenge for large BESSs because of the vast number of LIB cells installed to reach high capacities in BESS. A 200 kWh BESS, for instance,

[5] "The most common and fundamental source of capacity fade in successful Li-ion batteries (which manage to resist degradation over hundreds of cycles) is the loss of lithium to the solid electrolyte interphase (SEI), which typically forms at the negative electrode during recharging. Initially, SEI formation protects the electrode against solvent decomposition at large negative voltage, but over time it leads to a gradual capacity fade as the SEI layer thickens." [67]

with a capacity of 3,000 mAh and a nominal voltage of 3.6 V requires a minimum of 18,518 LIB cells to reach the capacity requirement of 200 kWh.

In addition, the following list includes the most important rules and pre-norms for LIB BESSs:

- DIN EN 62619 – Safety norm for batteries
- DIN EN 62109 – Safety norm for PE
- DIN EN 50272-2 – Safety for stationary battery systems
- VDE AR-E 2510-2 – SES in LV grids
- VDE AR-E 2510-50 – Stationary LIB BESS
- ICE 62485-2 – Safety for stationary battery systems
- ICE 61427-1 – General requirements and test procedures for photovoltaic (PV) BESS
- Sicherheitsleitfaden Li-Ionen Hausspeicher – German safety guide for LIB BESSs [68]
- BATSO 02 – Test procedures for certified transport of LIB
- UN 38.3 – Test procedures for certified transport of LIB

Subchapter 2.2 provided a brief overview of the safety literature relevant to producing, operating or planning LIB BESSs. These documents are based primarily on the knowledge of LIB cells and their safety, which was addressed in Subchapter 2.2.1 as a brief introduction to further understand the matter.

2.3 Legal Framework for BESSs

On battery storage in the German electricity market

Several business actors and compatible APMs for MP-BESSs emerge when considering the German energy market rules, laws, regulations, and directives, as discussed in the following chapters. In addition to legal and regulatory framework conditions, the economic framework conditions also have a significant impact on the success of new technologies, i.e., the MP-BESS as an MPT-BESS variant.

Table 5 – Remunerations of stationary BESSs concerning charge and discharge as of 09/2016.

	Charge	Discharge
Feed-in remuneration	No	With the purchase of renewable power: Yes, possibly pursuant to § 19 (4) EEG[6], if no feed-in remuneration is used before. With the purchase of conventional power: No.
Remuneration for relieving the grid	No	With the purchase of renewable power: Yes, possibly pursuant to § 18 (1) StromNEV[7] (In the future, only as long as no feed-in remuneration pursuant to § 19 EEG is used.) With the purchase of conventional power: Yes, possibly pursuant to § 18 (1) StromNEV.

The investment costs and various other parameters have an economic impact on the business models and include inter alia, electricity costs and renewable energy feed-in remuneration. However, the business models presented in Chapter 6 include a specific economic calculation,

[6] Renewable Energy Act

[7] Electricity Grid Charges Ordinance

and the investigations in Chapter 5 do not include the framework conditions. Economic calculations for the described models are not included because regulations and governmental directives change so quickly that this work would lack relevance in the future. Moreover, the possibilities for business models will generate interest for further research in this area.

Furthermore, because a large number of parameters and their individual ranges depend on each other, the results of a broad sensitivity analysis on economic performance may be insufficient because of significant uncertainties in the framework modeling. Thus, only fundamental thoughts on MPT-BESSs in Germany, specifically MP-BESSs, and business models functioning under current (August 2016) conditions are proposed.

Table 6 – Taxes, apportionments and levies for stationary BESS charge and discharge in Germany as of 10/2016 [69].

	Charge of BESS	Discharge of BESS
Apportionment for renewables	Yes, as long as § 60 (3) sentence 1 EEG is not fulfilled.	No.
Network charge	No, pursuant to § 118 (6) EnWG[8] (for 20 years).	No, pursuant to § 15 (1) sentence 3 StromNEV.
Allocations and costs considering network charges	In general, yes, according to BK4-13-739 (Federal Network Agency).	In general, no.
§19 StromNEV-levy	Yes, e.g., 0.237 ct/kWh, except for § 19 (2) sentence 15 StromNEV.	No.
Concession	Yes, max. 0.11 ct/kWh, except for § 4 (1) sentence 1 KAV.	No.
Heat power levy (KWK[9]-Umlage)	Yes, over 100,000 kWh/a max. 0.05 ct/kWh, except for § 9 (7) sentence 1 KWKG.	No.
Offshore levy	Yes, until 1,000,000 kWh/a max. 0.25 ct/kWh, amount of electricity above max. 0.05 ct/kWh, except for § 17f (1) sentence 2 EnWG.	No.
AbLaV levy[10]	Yes, 0.006 ct/kWh, except for § 18 (2) sentence 2 AbLaV.	No.
Tax on electricity	May be pursuant to § 9 (1) Nr. 2 StromStG, 20.50 €/MWh pursuant to § 3 StromStG (particularly with conventional power). No, pursuant to § 9 (1) Nr. 1 StromStG in conjunction with § 19 (1a) EEG with purchase of renewable power without feed-in remuneration.	No, pursuant to § 1 (1) sentence 3 StromStG[11].

[8] German Energy Act

[9] Combined Heat and Power Act

[10] Ordinance on Agreements Concerning Interruptible Loads

[11] Electricity Tax Act

Furthermore, this subchapter provides a brief overview of the primary stakeholders for BESSs, specifically MP-BESSs, in Germany. In addition to their interdependence on the storage system, suitable APMs and their benefits for each stakeholder are introduced. However, a statutory definition of BESSs does not exist in Germany [70, 71], and the draft of the Renewable Energy Sources Act 2017 does not contain further information on this topic [72]. A patchwork of several laws, regulations, and directives constitute the legal point of view for BESSs in Germany, in particular, regulations for charging and discharging. Table 6 and Table 5 provide a brief overview of stationary BESSs in Germany and their remuneration and taxation when they are technically integrated into the network [69, 73].

On stakeholders in the electricity market

The distribution of electricity requires several grids at different voltage levels. Firms operate these grids via reinforcement, maintenance, and expansion. These companies are commonly known as grid operators. As mentioned before, grid operators in Germany are split up into transmission system operators (TSO) and regional or local distribution system operators (DSO) under the German Federal Network Agency (BNetzA) or the European Network of Transmission System Operators for Electricity (ENTSO-E). These can be compared to regional transmission organizations (RTOs[12]) and independent system operators (ISOs[13]) under the Federal Energy Regulatory Commission (FERC) or the North American Electric Reliability Corporation (NERC) in the U.S. Their objective is to provide an affordable, sustainable and reliable supply of electricity and integrate renewable energies, as per § 1 of the German Energy Act, EnWG. (“Energiewirtschaftsgesetz”) [74].

There is a natural monopoly on electricity grids because of the high fixed cost, CAPEX, for setting up grids and the comparably low operating expenses, OPEX. If there were multiple vendors, each would have to bear the fixed costs of its grid, which would result in an increase in the average total cost. Monopolies are caused by the increasing returns vs. the falling average total cost. The awarding of concession contracts results from a natural monopoly in which grids are tendered every 20 years per § 46 of the German Energy Act [74, 75]. In this context, grid operators are given the right to use the public domain to provide end users with electricity and can lay and operate power lines, transformers, and other grid assets.

2.3.1 Transmission System Operators in Europe

Since 2009, the European Network of Transmission System Operators for Electricity (ENTSO-E) and NERC in the U.S. have dealt with the network codes, security, and reliability of the grids and with coordination and information [74, 76–78]. Previously, other associations represented the TSO in most of the countries in continental Europe.

The Union for the Coordination of Production and Transmission of Electricity (UCPTE) was active from 1951 until 1999 when it became the Union for the Coordination of the Transmission of Electricity (UCTE) and finally the ENTSO-E. The fundamental rules for the four German TSOs (50Hertz, Amprion, TenneT TSO and TransnetBW) are in TransmissionCode 2007 [79], and the

[12] A regional transmission organization in the U.S. is an electric power transmission system operator (TSO) which coordinates, controls and monitors a multi-state electric grid.

[13] An independent system operator is similarly an organization formed at the recommendation of the Federal Energy Regulatory Commission (FERC).

ENTSO-E is currently developing general rules for the overall grid territory in Europe. After the Agency for the Cooperation of Energy Regulations (ACER) gives the “Framework Guidelines on Electricity Grid Connections” to the TSOs, the TSOs will develop the network codes [80]. However, the ACER and the European Commission will have the chance to reject the network codes according to Articles 6 and 8 of Regulation (EC) No 714/2009 and Directive No 2009/72/EC [78, 81].

Nonetheless, the TSOs are responsible for the optimal and secure operation, maintenance and, if necessary, expansion of their grids in their respective areas. Therefore, several rules for TSOs already apply cross-border. In this context, TSOs provide ancillary services such as frequency control, voltage control, restoration of supply systems and operation management [79]. Control power is necessary to maintain the balance between electricity generation and consumption in real time. Control power is also an important part of meeting the TSO obligations, which turns out to be a suitable APM for MP-BESSs and BESSs.

2.3.2 Distribution System Operators

Problems occur partly in German grids at lower voltage levels (20 kVAC down to 400 VAC) because of the massive expansion of PV systems in Germany, which has resulted in a change in the load flow at various times of the year and overloading of transformer stations and lines. Neither the transformers nor the lines were designed for these situations [82]. Therefore, DSOs must extend, reinforce and/or renew existing installations in these cases. Using BESSs, power input peaks can be reduced to achieve a delay or even a waiver of the extension. According to [83], BESSs could be an alternative to an upgrade investment. This suggestion leads to the APM of “relieving the grid,” and the DSOs profit from BESSs.

2.3.3 Energy Supply Companies

Energy Supply Companies (ESCs) generate and sell power, but they do not possess the grids because of legal provisions concerning unbundling, as per §§ 6 et seq. of the German Energy Act [74] and Art. 2 No. 21 Directive 2009/72/EC [81]. In this context, the German Energy Act contains rules for accounting, informational, organizational and legal unbundling with the aim of strengthening the competition [74]. At ESCs, a so-called balancing group manager is responsible for regulating the supply and demand for electricity in 15-minute intervals for each balancing area in his respective fields of interest according to the § 4 (2) regulation on electricity feed-in to and consumption from electricity supply grids – Stromnetzzugangsverordnung[14] (StromNZV). To fulfill this task, ESCs depend on load and generation forecasts. Therefore, participating in the wholesale of electricity is indispensable because of the lack of perfect forecast models. German ESCs use spot and forward markets for the European Power Exchange (EPEX) and European Energy Exchange (EEX) for electricity exchange [84]. Long-term futures markets are used for planning and hedging, and short-term day ahead or intraday markets help balance electricity when there are forecast errors. In addition to reducing the high purchase prices in the spot market using spare power from the BESS, arbitrage between times of high and low electricity costs is possible for an APM using the available capacity of the BESS.

[14] Electricity Grid Access Ordinance

2.3.4 Solar Power Plant Operator

In general, even small solar energy plant operators are regarded as ESCs (§ 117a of the German Energy Act 85), but they have different interests for using a BESS. Temporary storage of surplus PV energy to decrease their cost of electricity is their main concern. According to the grid parity for solar energy, it is possible to generate the necessary margins for refinancing the BESS [69, 86–89] instead of using grid energy. Grid parity occurs when an alternative power source can generate power at a levelized cost of energy (LCOE)[15] that is less than or equal to the price of purchasing power from the electricity grid, which was the case for private households with PV systems smaller than 30 kW in Germany in 2011. The average retail price of electricity was higher than the feed-in remuneration. Nevertheless, several studies and papers [26, 83, 91, 92] show that the exclusive use of this specific APM with a BESS is not profitable under the current framework conditions in Germany. For example, neither small home storage systems nor large BESSs have a positive return on invest (ROI) from storing surplus PV energy because of the low utilization ratio at night and during the winter [92]. In addition to the economy, several other facts are also crucial. According to [93], ideological reasons, such as the contribution to the energy transition, influence investment decisions on BESSs. According to [93], 34,000 BESSs are currently installed in Germany and are working as residential storage systems.

2.3.5 Power Customers

End users, particularly power customers, usually show interest in BESSs only if there is a reduction in their electricity price. A positive ROI from participating in the BESS in any way is desirable. In concrete terms, this means the either property or possession of the BESS or an electricity tariff attached to the BESS that results in lower prices for the end users is of interest to this group. This group of stakeholders is divided into two subgroups based on their power consumption. Households in Germany do not have to pay a special power price in addition to the energy price, but a special rate is compulsory for an annual consumption of at least 100,000 kWh [94]. Thus, large power customers have additional interest in peak shaving or peak shifting. Because of the legal and regulatory framework conditions, the location of the BESS must be on the company site, which is not compatible with most APMs. Therefore, reducing the energy price is the subject of this work.

2.3.6 Municipality

Municipalities benefit from BESSs through concession and commercial taxes, but they can also act as power customers. The latter is not given a separate mention, but it is included in the previous chapter. At nearly 44 billion Euros, in 2014 the commercial tax is the largest source of income for German municipalities [95] (p. 267). Under the German Trade Tax Act ("Gewerbesteuergesetz"), the level of tax depends on trade earnings, the local rate of assessment and legal forms [95–97] and can vary between different regions. The municipality itself is authorized to charge a duty for the right to use the public domain to provide end users with electricity and for laying and operating power lines, transformers, and other grid capacities. [74, 98]. The taxes and duties differ among themselves in terms of location, but there is a

[15] "The Levelized Cost of Energy(LCOE) is defined as the total lifetime cost of an investment divided by the cumulated generated energy by this investment." [90]

consensus that the operation of BESSs represents an economic advantage for each municipality.

3 Application Concepts and Stakeholder Analysis

This work seeks to identify the applications best suited for BESSs. Therefore, Chapter 3 lists the major applications for BESSs that are currently discussed in the literature in alphabetical order, there is no preference expressed due to the order. The applications for BESSs can be sorted based on their position in the electric value chain or their source for economic value, e.g., an application serving a purpose when generating renewable energy, i.e., renewable energy firming.

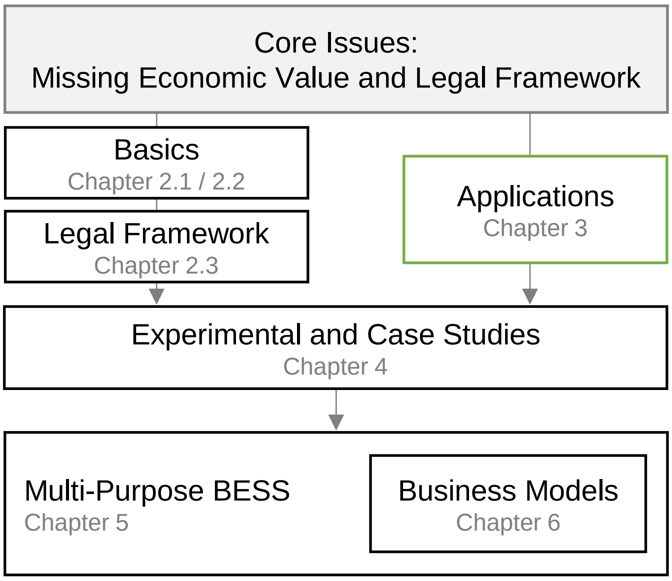

Figure 15 – Work progress in Chapter 3.

A review of the literature shows that the absolute number of applications ranges widely, and a common understanding of applications for BESSs is absent. However, this result also indicates the multi-purpose functionality of BESSs. Additionally, the application definitions for BESSs are strongly influenced by physical and technical parameters [21, 34, 37, 41, 99–108]. For a better overview, Figure 16 depicts BESS applications based on their source of economic value, location in the electrical supply chain, and area of service. The figure depicts the legal entity for which a certain value can be created and is comprised of independent system operators (ISOs) and regional transmission organizations (RTOs), customer services and utility services. A further differentiation is made between the location in the electric supply chain, including i) generation, ii) transmission, iii) distribution and iv) behind-the-meter use of electricity and the economic value source. As the literature studies indicate, any APM can be categorized by its economic value source [109], which can be classified into four different economic value sources: i) arbitrage, ii) power quality, iii) power reliability and iv) an increase in existing assets. A comprehensive analysis can lead to a variety of possible interpretations and arrangements for the given figure. However, the given arrangement seems to be appropriate for the vast majority of literature and expert knowledge, and it serves in this thesis to provide better interconnection of APMs and clarification of APMs in each contextual dependency.

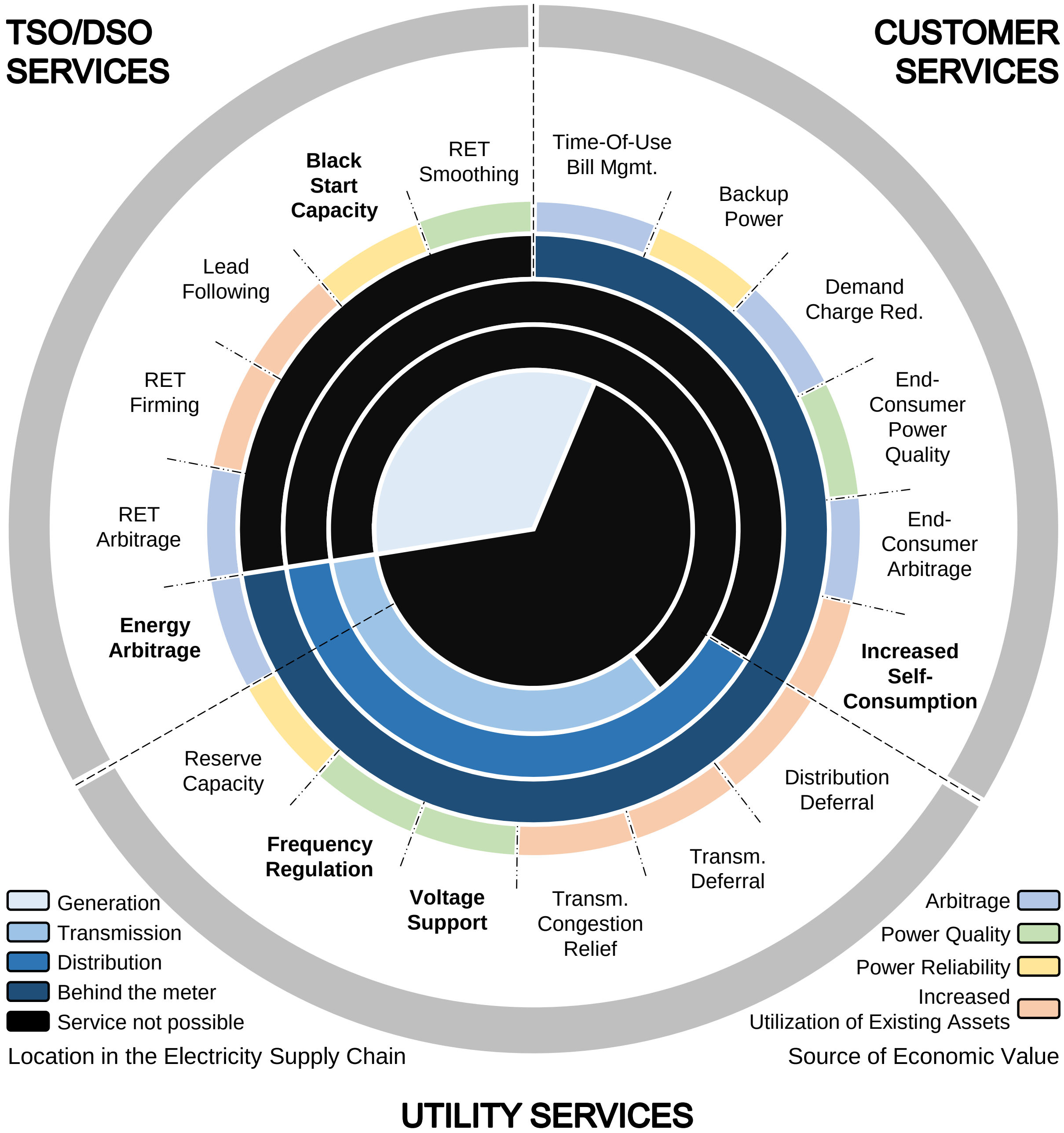

Figure 16 – Applications for BESSs according to the source of economic value, location in the electrical supply chain and area of service. APMs marked in bold are investigated in Chapters 3 and 4. Based on [110] and [111].

The following material provides a general overview and review of possible applications for BESSs. Because of the flexible configurations regarding power output and energy content, LIB BESSs can serve numerous APMs. While Chapter 2.3 explained specific use cases by outlining the concepts for BESSs under certain circumstances, the following is isolated from any obligations and focuses on the content of the solicitation and whether a BESS is capable of serving such demand and to what extent. Each application will be described by first outlining the underlying problem or incentive to operate a BESS. This content will be followed by an assessment of how the elucidation would be designed with and without a BESS, and it will end in an exploration of benefits from a BESS for the explained purpose. Table 7 lists the related subchapters for a general introduction to each APM and the related case study subchapters.

Table 7 – Overview of subchapters introduction application modes (APM), case studies, aging behavior analyses and abbreviations used in this thesis.

APM	Subchapter			
	Introduction	Case Study	Aging Behavior	Abbreviation
Black Start Capacity	3.1			BSC
Energy Market Participation	3.2	5.2		IDM
Grid Quality	3.3	4.3, 5.2	5.4	GRID
Island Operation	3.4	4.7		ISLAND
Secondary Control Reserve	3.6	5.2	5.4	SCP
Primary Control Reserve	3.9	4.6		PCP
Tertiary Control Reserve	3.7			TCR
Residential Home Storage	3.5	4.5, 4.6	5.4	SELF
Peak and Load-Shaving Services	3.8	5.2		GRID
Uninterruptable Power Supply	3.10			UPS

3.1 Black Start Capacity

BESSs can provide black start capacity/capability with a predefined V/f-controlled voltage and frequency characteristic. In addition, swarms of smaller BESSs have the ability to participate and run a black start on their own. The pure provision of a black start capacity for a BESS is not promising because of missing business models. However, the knowledge that BESSs are capable of accommodating black start scenarios is an asset for future grid operations in which rotating masses will significantly decrease in quantity [41, 108]. Table 8 shows typical values for a BESS providing black start capacity, based on expert interviews in [106].

Table 8 - Characteristics of the APM Black Start Capacity for BESS. Based on [106].

Parameter	Value	Unit
capacity	130 – 3000	kWh
power	130 – 3000	kW
cycles per year	1	n
DOC	deep	
mean SOC	high	

3.2 Energy Market Participation

The participation of BESSs in energy markets is commonly discussed. The ability to switch between power provision and consumption leads to the overall idea that BESSs may be suitable for participation in energy markets [112] and arbitrage operation. However, the integration of

BESSs in energy markets will be determined by market regulations and rules. Generally, arbitrage generates revenues and profits by buying electric energy at low prices and selling at high prices. The potential revenues scale with the number of respective cycles over a given time frame. Thus, if storage aging is neglected, the more cycles an arbitrage operating BESS runs in a given timeframe, the higher the revenue is. The mentioned cycles mostly occur as small and frequent cycles during the day time. It has been shown that different EESs and BESSs can achieve positive returns on arbitrage. Technological characteristics, not market price volatility influence the revenues for these [113]. However, in general, BESSs are not yet viable for providing arbitrage as a single application because of the necessity for active electrochemical storage, which drives costs relative to other technologies that are more costly in energy-specific pricing [53]. Table 9 shows typical values for a BESS operating APM arbitrage.

Table 9 - Characteristics of the APM arbitrage for BESS. Based on [106]

Parameter	Value	Unit
capacity	5 [107] (2 – 4000 [100])	MWh
power	1 [107] (1 – 500 [100])	MW
cycles per year	w/o (400 – 1500)	n
DOC	deep [114]	
mean SOC	high	

3.3 Grid Quality

The integration of BESSs in electricity grids can lead to significant improvements in grid quality and reduce maintenance or classic grid reinforcement by adding line capacity or transformers to existing grids. Selected grid quality criteria are described in the following sections. In LV grids, several BESSs can be used to improve grid quality, e.g., unloading the grid in times of high power flow. Transformer load reduction is one of the key roles BESSs can fulfill. With power ratings of a few hundred kW up to several MW, BESSs can be implemented for transformer-unloading purposes even in larger grid chapters with substantial demand. The impact of BESSs comes from charging in times of high backfeeding load flow and discharging in times of high-demand load flow. An adapted operational strategy allows BESSs to significantly reduce the transformer load in times of high load flows. Line loading is a parallel benefit BESSs can provide. When BESSs are interconnected between a powerful distributed generation unit (DG), e.g., a large PV field and the transformer station, the BESS unloading of the transformer influences the direct connecting line with the same power and energy from which the transformer is relieved. For rural regions in particular that lack growth in terms of inhabitants or industry, the connecting lines include small safety additions to the line size and transformer size. Subchapter 4.3 provides insights on a case study that shows the dangers of line and transformer sizing for vast RET installations in the mentioned area over the past decade. Additionally, the limits for node voltages, defined in DIN EN 50160, are the main drivers for grid reinforcement and extension, particularly in rural regions [115]. BESSs are able to reduce the voltage at critical points in the grid by drawing real power from the grid, as depicted in Figure 17. With a typical ratio of R/X = 2.5 for LV grids [66], a variation of the active power P has a larger influence on the voltage than the feed-in of reactive power from DGs [116], which is required by VDE-AR-N 4105. In addition to the aforementioned three grid operations, BESSs can serve to improve grid quality. Reactive power injection is another possible service to improve grid quality [117, 118].

In general, power transmission losses increase with the square of the current flow, and the affected cables warm up. The increased cable temperatures affect the efficiency of the supply and lead to accelerated aging of the operating materials. For this reason, it is desirable to reduce the losses by decreasing the load peaks. A common method to achieve this is the laying of new cables. The costs for 1 to 10 kV cables (system price including earthworks) are estimated at 350 to 500 euros/m. The excavation work is mainly responsible for the high cost. (Note: The given figures are only indicative values; the exact values vary for each individual case.) Influencing the demand is a cost-effective measure to reduce the load peaks. For this purpose, demand response procedures could be used in which the demand is automatically reduced based on the load. However, this approach requires the installation of appropriate control devices at the customer's site. In the future, it may be possible to limit the demand via variable grid charges. This method will require the rollout of a smart-meter-based infrastructure. Energy storage systems are already available and can contribute to a reduction in load peaks. Charging and discharging energy storage systems can be used to avoid load peaks and equalize the load demand curves. However, it is not certain to what extent a reduction in the grid losses can be achieved because of the power losses associated with the storage operation.

In addition to the grid voltage, there are other grid services that BESSs can potentially provide. Short-circuit power is relevant for electricity grids and their short-circuit protection. It is a rating value and is given as an apparent power. Expressed mathematically, the short-circuit power S_k is the product of the short-circuit current I_k, nominal voltage U_n, and chaining factor. The short-circuit power is a rating value used to quantify the strain on electrical systems. A high short-circuit power is a measure of the voltage quality and interference immunity of a power grid. The expansion of a power grid can influence the short-circuit power. Technically, this effect can also be realized by means of a decentralized grid structure. A high short-circuit power is also crucial for safe grid operation. The protection systems currently installed in the grid presuppose a certain short-circuit current, implying short-circuit power. Furthermore, sufficient short-circuit power is relevant for motor loads. Starting these loads is not possible without sufficient power. With regard to the operating materials, the short-circuit power is a design parameter in addition to other influences. The highest short-circuit powers occur on bus bars when they are fed by multiple sources with low impedance. In particular, generative feeders, such as asynchronous and synchronous generators, significantly contribute to the short-circuit power. Unlike generative feeders, systems based on inverters make only a small contribution to the short-circuit power. In general, the short-circuit current is in the range of the nominal current. Decentralized generation systems, in particular PV systems, fuel cells or wind energy systems without a gearbox, feed their power into the grid through an inverter. Thus, the individual system makes only a small contribution to the required short-circuit power. Accordingly, the contribution rises with the number of involved plants. Nevertheless, it is not certain that the power is sufficient for a reaction of the safety systems. Electrochemical energy storage systems are an additional technical option to compensate for a possible deficit in short-circuit power. As with all inverter-based systems, the individual battery storage system delivers only a small contribution, but a significant, greater potential can be assumed for multiple plants, i.e., as a supplement to PV systems. LIB BESS can be overloaded heavily for short durations, thus the final short-circuit power per BESS systems depends on the maximum current the PE can provide.

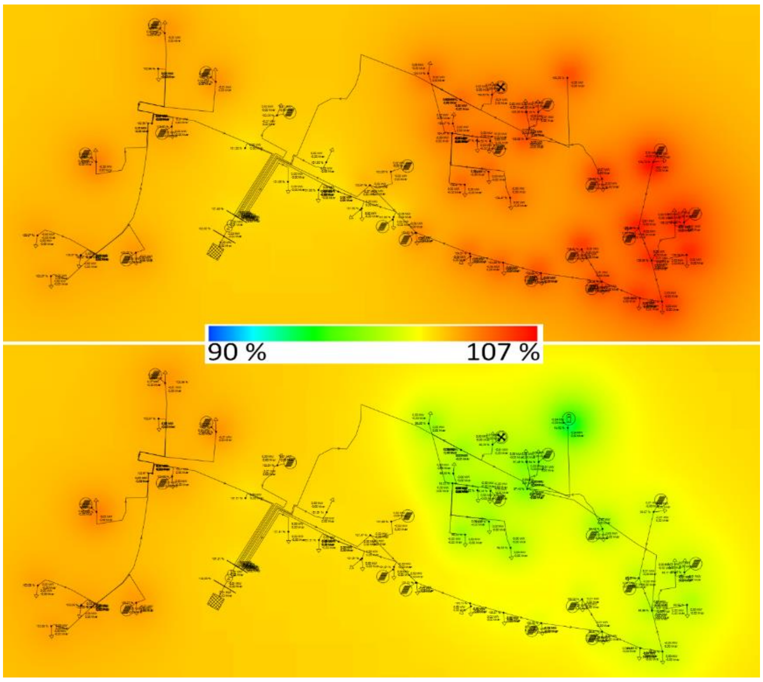

Figure 17 – Voltage reduction with BESSs in an exemplary LV grid (backfeeding scenario). Top: No BESSs installed; major voltage limit violations are observed. Bottom: BESSs installed, and an additional connection of 2 stub lines to a ring line; major improvements in the voltage can be observed. Coloring depicts the derivation from the nominal grid voltage. [39]

Third, voltage fluctuations may be reduced by BESSs in the future. Voltage fluctuations, which include flickers and other variations, are addressed in EN 61000-3-3 (June 2006). Flickers are voltage variations that can cause a fluctuation in electricity consuming objects. Flickers occur because of the finite internal impedance of the grid, causing a voltage drop due to the load current of the device. As a consequence of these power supply voltage fluctuations, changes in the luminous flux of incandescent lamps are observed. This effect cannot be perceived in fluorescent lamps and LEDs because their electronic ballasts compensate for these fluctuations. The appearance of flickers can be attributed to different causes. Voltage drops can arise because of a pulsed power input, which occurs during the operation of hob units, hair dryers, washing machines, power tools, air-conditioning systems, and many other devices. However, inrush currents can also be responsible, and these occur after an interruption during voltage recovery. In typical load cases with many electronic power supply units, all of the smoothing capacitors are charged simultaneously, which results in a current overload. Inrush current-limited devices provide a remedy, e.g., the installation of an NTC resistor in each device. Switching on large asynchronous machines can also lead to voltage drops. The current amplitude is determined by the switching angle and the grid impedance. From a network perspective, larger short-circuit ratings can be used to avoid this phenomenon. For example, the use of transformers with a smaller u_k (4% instead of 6%) can achieve this mitigation. In the wind energy generation field, flickers can be attributed to switching operations, tower shadows, tower disturbances, blade angle errors, cross flows, wind shears and fluctuations in the wind speed. Electrochemical energy storage systems can remove flickers. Battery storage systems are dependent on the demand, but they are independent of the location. Short-term voltage variations due to fast changing loads/generation (feed-in/consumption of active and/or reactive power in the seconds range) can be compensated. Table 10 shows typical values for a BESS operating APM grid quality, based on expert interviews in [106].

Table 10 - Characteristics of the APM grid quality for BESS. Based on [106].

Parameter	Value	Unit
capacity	500 [107]	kWh
power	1 [107] – 10 [100]	MW
cycles per year	200 - 600 [106]	n
DOC	deep (refer to Figure 63)	
mean SOC	low (refer to Figure 63)	

3.4 Island Operation

Numerous regions worldwide are facing major challenges due to the increasing electricity demand from rising populations and industry. Many regions, especially those with a large number of scattered islands, are strategically planning future energy production. BESSs for island operations are of interest to help overcome the challenges associated with energy demand and provide an environmentally suitable solution. BESSs operating on islands can significantly ease the provision of electrical energy. No matter how many RET installations are in place, the vast majority of energy is still produced by fossil fuel generators. A fully autonomous BESS operating in island APM is able to build up, hold and support an electric grid and act as a generator and frequency balancing the load. PE units and the system technology necessary for such actions are available in industry markets already. Basically, a BESS operation in island APM is a combination of a series of other APMs, i.e., ancillary services, peak-shaving, and RET shifting, and will not be explained in further detail. Table 11 shows typical values for BESS island operation.

Table 11 - Characteristics of the APM arbitrage for BESS. Based on [106]

Parameter	Value	Unit
capacity	< 1	MWh
power	< 100	kW
cycles per year	400	n
DOC	deep [114]	
mean SOC	high	

3.5 Residential Home Storage

One of the well-known, current applications for BESSs is their use in a residential configuration, corresponding to the installation of a BESS in a household with a PV system. Since the early 2000s, there have been huge innovation steps toward better efficiency and major cost decreases in PV technology. In addition, several countries have implemented major incentive programs and have mandated acts and regulations benefitting and promoting PV systems over other energy producing facilities. Residential BESSs increase the self-consumption of self-produced energy in households, typically based on the desire for lower energy costs or driven by ecological motives.

The Speichermonitoring 2016 report [93], a nation-wide analysis on private household LIB BESSs in Germany, showed that 80% of LIB BESS owners are aware of the current low economic value of BESSs; however, the owners purchased BESSs to protect their homes from future increases in energy prices. In addition, this research has shown (n = 927) that customers are willing to buy BESSs because of cheaper electricity. It is currently not clear whether a massive installation of BESS in residential homes with PV systems would be environmentally beneficial and reduce CO_2 emissions. The vast majority of installed BESSs in the European grid do not involve positive economics, which leads to the assumption that ecological motives play a major role in BESS-buying decisions.

There are clear benefits in terms of electricity cost savings for individual customers. The BESS stores energy any time a surplus of renewable energy occurs locally and provides the stored energy in times of high loads and lower production. The basic figures to calculate these benefits are known as the self-consumption rate (SCR) and self-sufficiency rate (SSR). Both are coupled to the overall consumption of the generated renewable energy in a specific household and always refer to a yearly timeframe. The SCR calculates the self-consumed energy with respect to the overall generated renewable energy in the same period. Thus, the full consumption of all of the generated renewable energy equals an SCR of 100%.

The overall benefit of a residential BESS, regardless of investment costs and subsidies (which range significantly between countries and markets), can be described as the household's total electricity cost$C_{electricity_{total}}$. The total electricity cost $C_{electricity_{total}}$ is the yearly consumed energy, $E_{consume}$, multiplied by the household's electricity price or cost, C_{kWh}, per kilowatt-hour.

$$C_{electricity_{total}} = E_{consume} * C_{kWh} \tag{9}$$

With a PV system, a household's yearly consumed electricity $E_{consume}$ is not the direct electricity demand of the household but is dependent on the direct consumed solar energy, E_{solar}. In addition, the solar energy, which cannot be used by the household itself, will be fed E_{feedin} into the grid. The fed in solar energy multiplied by the feed-in remuneration C_{feedin} represents an additional income for the household. An additional cost derives from the curtailment of surplus solar energy. Whenever the possible solar feed-in power exceeds the grids feed-in limitations, which are set by regulators, this power will be curtailed. Thus, the curtailed energy $E_{curtail}$ has to be subtracted from the total possible feed-in energy E_{feedin}. The household's total electricity cost is now as follows:

$$C_{electricity_{total}} = (E_{consume} - E_{solar}) * C_{kWh} - (E_{feedin} - E_{curtail}) * C_{feedin} \tag{10}$$

With a BESS, the total electricity cost is additionally reduced by the amount of solar energy that can be stored for later use by the BESS $E_{BESS_{solar}}$ to prevent the curtailment of solar energy. Thus,

$$C_{electricity_{total}} = \left(E_{consume} - E_{solar} - \left(E_{BESS_{solar}} * \eta_{BESS}\right)\right) * C_{kWh} - \left(E_{feedin} - E_{curtail}\right) * C_{feedin} \tag{11}$$

The above description serves as a general description of the benefits and fundamental understanding of BESS operation in a household. The aim of BESSs in single-family houses, as mentioned above, is to increase the household's SCR of solar energy consumed. The SCR is given by

$$SCR = \frac{E_{solar}}{E_{PV}} \tag{12}$$

where the self-consumed solar energy is divided by the overall solar energy E_{PV} production. The SCR describes the amount of PV energy that can be consumed locally as a percentage in respect to the overall solar generation [119]. A second variable, the SSR, quantifies the benefit of the PV system by describing how much of the load demand can be covered by local PV energy. The SSR is calculated as the ratio of E_{solar} and the total load demand E_{load}.

$$SSR = \frac{E_{solar}}{E_{load}} \tag{13}$$

Both variables, the SCR and SSR, can be calculated for residential setups with a BESS. In that case, the SCR and SSR are given by

$$SCR = \frac{E_{solar} + (E_{solar_{\mathrm{BESS}}} * \eta_{BESS})}{E_{PV}} \tag{14}$$

$$SSR = \frac{E_{solar} + (\mathrm{E}_{solar_{\mathrm{BESS}}} * \eta_{BESS})}{E_{load}} \tag{15}$$

where $E_{solar_{BESS}}$ reflects the overall energy which can be stored by a residential BESS. Table 12 shows typical values for a BESS providing APM SELF.

Table 12 - Characteristics of the APM SELF for BESS. Based on [106].

Parameter	Value	Unit
capacity	3 – 45	kWh
power	1 – 15	kW
cycles per year	300 - 400	n
DOC	deep	
mean SOC	low / high	

On a simple operation strategy

A greedy algorithm is an algorithm that always takes the best immediate, or local, solution while finding an answer. *Greedy algorithms find the overall, or globally, the optimal solution for some optimization problems, but may find less-than-optimal solutions for some instances of other problems.* In the context of residential BESSs, a greedy algorithm follows the logic of storing any surplus solar power provided as soon as possible and providing any available energy from the storage as soon as there is a lack of solar power. The algorithm is simple as follows

$$P_{BESS} = P_{PV}(t) - P_{load}(t) \tag{16}$$

where P_{BESS} is the BESS power, P_{PV} the power from the solar systems and P_{load} the household's load. Figure 18 depicts such a storage behavior whit the BESS charges during early day hours as soon as $P_{PV}(t) > P_{load}(t)$ until the BESS is fully charged at 100% SOC and discharges as soon as $P_{PV}(t) < P_{load}(t)$ until the BESS is fully discharged to 0% SOC.

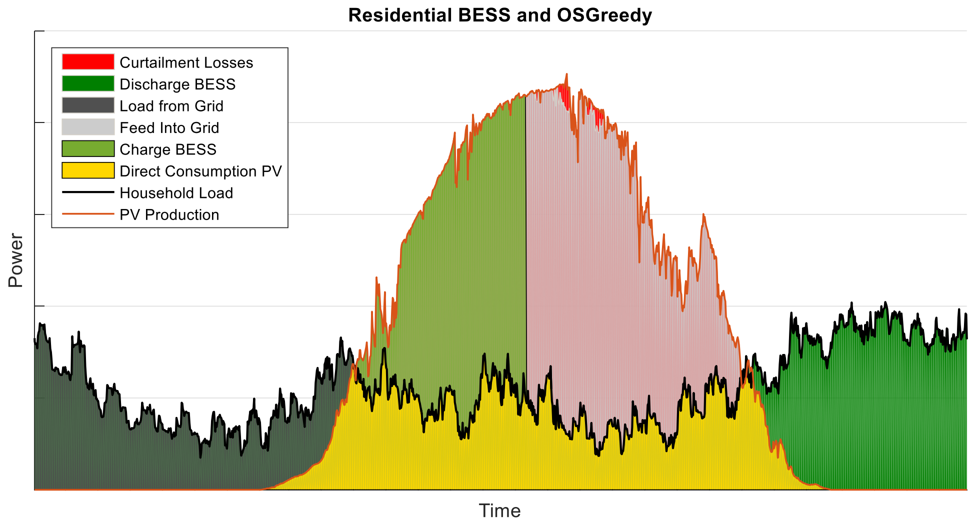

Figure 18 – Exemplary operation of a BESS operation greedy algorithm in a residential setup over one day from midnight to midnight. Curtailment losses may occur during peak solar insulation times and reduced household loads due to curtailment orders by the EEG law in Germany.

On a grid-friendly operation strategy

Because of the high number of installed PV systems, grid relief is a major point of interest for regulators, and grid operators since the installation of RETs showed a significant increase from 2012 to 2016. Forecasts from 2014 predicted a total installation of PV RET power in Germany of 50 GW by 2020 [120], and in 2016, a total of 39.85 GW had already been installed [121]. Because of the dependence of PV systems on solar irradiation, i.e., weather conditions, the predictability of these systems is lower than that of a fully controllable conventional DG, and simultaneous regional occurrences of high solar irradiation can lead to overloading of the power lines, transformers, and cables. During times of extreme load scenarios, e.g., times of relatively high insolation, the permitted voltage ranges or thermal thresholds of grid operating technical systems are violated [122]. A DSO's conventional reaction to solving such problems is grid expansion or reinforcement by adding line capacity, cable installation or upgrading transformers. An alternative to these conventional actions is the installation of storage capacity in the form of BESSs and, ideally, the grid-friendly operation of such systems. Therefore, policy makers, who regularly develop subsidiaries to deliver RETs into grids, have established maximum feed-in powers for RETs, e.g., PV systems. Installers of PV systems in Germany that want to benefit from subsidies must restrict their PV systems' maximum feed-in to 50% for a 20-year lifetime operation [123]. BESS installation under the aforementioned greedy operation is not capable of solving the maximum PV feed-in because the BESSs are fully charged in the early hours of the day. Therefore, two operating strategies have been developed [117] whereof one will be described briefly.

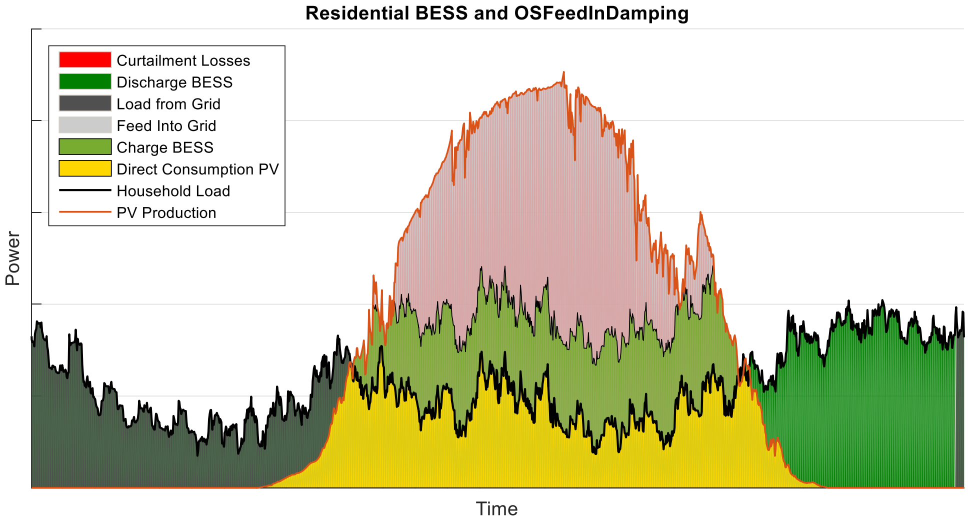

Figure 19 – Behavior of a residential BESS operated with the "feed-in-damping strategy."

The so-called feed-in-damping strategy, depicted in Figure 19, damps the feed-in power by storing the surplus feed-in throughout the day to ensure a maximum SOC of the BESSs by applying a nearly constant charging power, P_{BESS}. The constant charging power is calculated by dividing the spare BESS capacity $\left(SOC_{max} - SOC(t)\right) * E_{BESS}$ by the prediction of time to sunset, on the same day of operation [117]

$$P_{BESS}(t) = \frac{(SOC_{max} - SOC(t)) * E_{BESS}}{(t_{sunset} - t\ )} \tag{17}$$

The discharging behavior of BESSs operating in the feed-in damping strategy follows the same rules as the greedy operation described in equation (16).

3.6 Secondary Control Reserve

Control reserves are given in alphabetical order, and in Subchapter 3.5 a short introduction to providing reserves is provided.

Power producers are obliged to forecast their delivered quantities as precisely as possible. By doing so, the feed into the German power grid can be optimally planned, and the frequency of the power grid can be maintained at 50 Hz. In the case of an unexpected increase in the electricity consumption or capacity bottlenecks affecting the stability of the electricity grid, the control reserve is used. This reserve compensates for the fluctuations in the power grid, and a graduated regulation system is applied, i.e., primary control reserve (PCP), secondary control reserve (SCP) and minute reserve. In Germany, the four German TSOs are responsible for this regulation. In addition to the stability assurance, the control reserve is needed in case of an electricity oversupply or undersupply in the electric grid. If no suitable storage systems exist for such cases, a rapid down-regulation of power plants or the connection of additional consumers is necessary. In the case of a sudden increase in demand and an insufficient supply, the positive control reserve is used, and additional generation capacity is required. The compensation for an increased supply and a weak demand is called a negative control reserve. By storing or reducing the power generation, electrical energy can be taken from the power grid.

The worldwide available market is, particularly for quick-response participants, attractive for LIB BESSs. Markets worldwide tender these services differently, and regional influences in large grids (the U.S., e.g., [124]) lead to more diverse market structures, whereas smaller markets tend to have single-oriented and shared tenders for frequency control services (e.g., the EU). In the EU, the ENTSO-E is the entity for all transmission network operators in Europe; it closely follows the European Commission market design studies and effectively implements control markets. The markets and tenders in the ENTSO-E are the primary, secondary and minute control reserves [125]. Each market differs in terms of ramp-up speed and provision scheduling [126, 127].

The task of maintaining frequency stability is divided into different control stages:

- PCP for effective power balance, primarily via speed regulation by the electrical generators of the involved power plants.
- SCP to maintain the frequency stability in integrated grids, such as the ENTSO-E, for load flow management and load distribution.
- Minute reserve, also referred to as the minute control reserve, which is used for economic optimization during operation.
- Quaternary control reserve to compensate for the gait error, which is triggered by accumulated deviations from the main frequency over longer time periods.

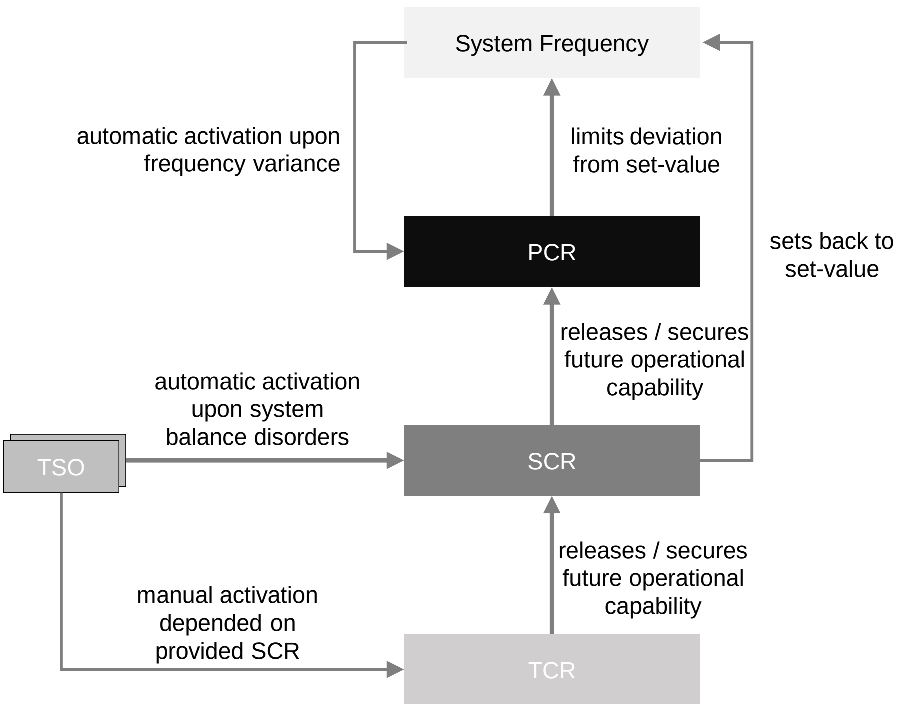

Figure 20 – Frequency control markets and tender activation under the ENTSO-E regulations in the UTCE European grid. Based on [128].

The graph describes the temporal deployment of the individual control reserves. The PCP must be fully activated within 30 seconds and be replaced by the SCP after 15 minutes. Further support is subsequently provided by the minute control reserve, which is also called the minute reserve. After approximately 60 minutes, a balanced load/current account balance should exist.

Similar to PCP, the provision of secondary control reserve/power (SCP) has an interesting application for several markets worldwide; the SCP power and energy support the grid and the physical balance between the energy consumption and production. Most markets differentiate between PCP and SCP based on regional necessities. While PCP is provided independently of the affected grid area grid-wide, SCP is only activated in the affected area. This strategy includes the provision to connect the grid areas where SCP has been activated directly. SCP is mostly justified by large amounts of renewable energies and imbalances in the grid. In Europe, SCP is needed to balance high feed-in energies from wind farms. The amount of necessary SCP is based on a comparison between the planned electricity consumption and production per grid control area, and the actual power flows between the grid control areas. Depending on the planned timetable for a grid control area and the real interexchange power between these and the overall grid frequency, the needed power for SCP is estimated in an automated process by the TSOs. Thus, the activation of SCP is automated, as is the activation of the systems providing SCP. Similar to PCP, SCP has activation times and other requirements for prequalification. SCP is offered in four different tenders: positive, negative, high tariff (HT) and low tariff (LT). The HT period is from Monday to Friday between 8 AM and 8 PM, and the low tariff period is valid on any holiday, weekend days and Monday to Friday between 8 PM and 8 AM. The prequalification requirements must be proven to the TSO in the area the SCP providing system falls. In Germany, for example, the minimum power requirement is 5 MW, which can also be offered by virtual connecting smaller entities. SCP, in contrast to PCP, differentiates between positive and negative control power in two different timeslots. Therefore, SCP is offered as four different products. In general, BESSs are able to provide SCP; however, correct proof of work and layout of the BESS topology must be designed accordingly [129]. Table 11 shows typical values for BESS providing secondary control reserve, based on expert interviews, market design rules [129, 130] and [106].

Table 13 - Characteristics of the APM SCP for BESS. Based on [106].

Parameter	Value	Unit
capacity	12 - 200	kWh
power	50 - 800	kW
cycles per year	400	n
DOC	flat (refer to Figure 64)	
mean SOC	low / high (refer to Figure 64)	

3.7 Tertiary Control Reserve

In addition to the PCP and SCP, the minute reserve (MCP), also called the minute control reserve, is used to compensate for fluctuations in the German electricity grid. It is activated after a lead time of 15 minutes. The MCR supports the electricity grid when the frequency drops significantly below 50 Hz or rises above 50 Hz. MCR is classified as either "positive" (compensation of power deficits) and "negative" (compensation of power surpluses) MCR.

Currently, flexible gas-fired power plants and pumped-storage power stations are mainly used. Additionally, co-generation plants or decentralized generation facilities, such as emergency power generators and biogas plants, are used. The MCR market is organized by the four German TSOs. The demand is covered within auctions. The TSOs are responsible for implementation, and they organize an invitation to tender via a common internet platform [131]. They are also responsible for the prequalification of the MCR providers. Prequalification of the reserve units (e.g., generation units or controllable consumer loads) is applied to each control zone separately. The connection TSO, in whose control zone the provider plant is connected, is responsible regardless of the voltage level [131]. MCR is tendered daily via the internet platform. The required minimum lot size is 5 MW. A pooling of smaller plants is possible to ensure the minimum power. Activation occurs via telephone over the course of an automated retrieval. The availability of the provided reserve can be secured by prequalified technical units of third parties' plants in the same control zone [131]. The auction sale occurs according to the respective capacity price. In contrast, the MCR is retrieved according to the energy price. In this way, manipulations from incorrect pricing are avoided. MCR provides a further application field for storage systems in the control reserve area. However, in the case of a power request, longer operating periods of the reserve plants have to be assumed. This approach usually requires sufficient storage systems or installed capacity. The application possibilities will be restricted if sufficient plants to secure the provided reserve are not available.

3.8 Peak and Load-Shaving Services

Peak and load-shaving describe the application to move power peaks in either the negative or positive direction from times of high load to times of low load. With reduced load peaks, grid stabilization is more likely, grid operations per regulation-time segment are less necessary, and end-users may profit from lower electricity costs. The time-dependent moving of power can be realized using BESSs operating on the same bus as the load or directly coupled to the load. In times of high load, the BESS stores surplus energy and releases that energy in times of low load. This approach can result in reduced electricity bills for customers by charging/discharging the BESS during load peaks [83]. Industrial energy consumers that require large amounts of power during operation times are often faced with special tariffs [132]. These factor the comparably high power demand with respect to the general load, which results in higher power and energy prices. Demand charges are therefore directly connected to the maximum power peaks, which are mostly measured over the course of a month or a year depending on the electricity market design. The basic principles for using a BESS for load-shaving are described in [132] and show in detail BESS size optimization and the optimal operation strategy for such systems.

The fundamental methods for this APM are described as follows:

$$\begin{gathered} P_{max,needed} = P_{peak} + P_{BESS} * \eta_{BESS} \\ E_{min,needed} = P_{peak} * \Delta t_{shave} \\ P_{peak} = P_{peak_{max}} - P_{base} \end{gathered} \tag{18}$$

for power and energy necessities. The maximum power, $P_{max,needed}$, that peak-shaving systems are forced to accommodate depends on the maximum power peak in the baseload, $P_{peak_{max}}$, and the system's losses. The minimum energy needed is the maximum power peak of the load divided by the occurring time period [133]. Table 16 shows typical values for a BESS providing peak shaving services.

Table 14 - Characteristics for a BESS providing peak shaving services. Based on [106].

Parameter	Value	Unit
capacity	0.25 – 25	MWh
power	0.05 – 5	MW
cycles per year	300 - 400 [114]	n
DOC	flat	
mean SOC	high	

3.9 Primary Control Reserve

In the German federal electricity grid, the nominal frequency is 50 Hz. The primary control reserve, also known as the primary balancing power, is used to compensate for unforeseen fluctuations. This control reserve must be fully activated within 30 seconds to prevent a power failure. The amount of balancing power required for the PCP depends on the size of the electricity grid and the network topology [134].

In the integrated European grid (formerly known as the UCTE network), the frequency gradient of the balancing power is approximately 20 GW per Hz deviation from the nominal frequency. To ensure frequency stability, approximately ± 3,000 MW PCP is maintained [135]. The power is usually provided by larger power plants in Europe, and these plants automatically react to minimal load fluctuations in the power grid. The demand for the German coverage area is approximately 520 MW [136]. The PCP is automatically activated. For control purposes, the corresponding generation facilities are connected to the TSOs. PCP is tendered by the TSOs at a weekly auction, which is the responsibility of the connection TSOs. The connection TSOs are the TSOs of the control zone where the PCP is fed into the grid by the provider. This action is independent of the voltage level, and the tender of the PCP is symmetrical, meaning that no separate tender exists for positive (power generation) and negative (power purchasing) action. Participation in the PCP market requires prequalification, which in turn requires proof of the technical ability to provide the service. Production facilities, energy storage systems, and controllable consumer loads are permitted as technical units. The connection TSO conducts the prequalification in their control zone and is the sole contractual partner of the provider. In the case of a quasi-stationary frequency deviation of ± 200 mHz, the power plant marketing PCP must be able to deliver the total amount of PCP within a period of 30 seconds, including the linear increase and decrease of the power provision and the ability to remain at that power state for up to 15 minutes. The available PCP, the so-called primary reserve control band, must account for at least 2% of the plant's rated output. If the frequency deviation is less than 10 mHz, the PCP will generally not be activated in conventional power plants. When using relatively dynamic systems, a control within the 10 mHz range is also feasible (See Figure 21). A provider that sells technical units in several control zones must have a respective framework contract with each relevant connection TSO. A successful prequalification with prequalified power that accounts for at least the minimum lot size is necessary for the conclusion of a framework contract. The framework contract is the prerequisite for participation in the joint tendering for PCP [134].

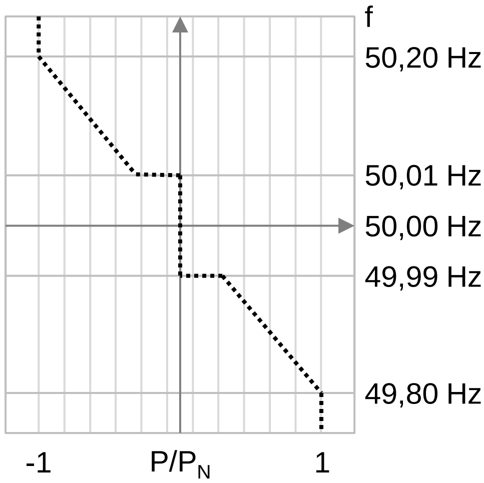

Figure 21 – Power-frequency characteristics for power suppliers in a PCP market with a 50 Hz grid according to the IGCC rules under ENTSO-E areas. Based on [137].

The TSOs' common internet platform has been used for implementation of the joint tendering since December 1, 2007. This common internet platform is used to publish the tender requirements, manage the bidding, and inform the providers about acceptances or rejections [134]. The minimum lot size was determined by the German Federal Network Agency on June 27, 2011, to be +/- 1 MW. However, it is permissible to ensure the minimum lot size by aggregating the power of several smaller units. Energy storage systems with fast response characteristics are ideally suited for providing PCP. They are considered an option to deliver PCP that may no longer be available from large power stations [134]. An activation call of a power supplier is outlined automatically and simultaneously decentralized for every market participant. The power-frequency characteristic (P-f-characteristic) must be fulfilled during the time a tender has been won. Figure 21 shows the characteristics of the UCTE grid. Inside the band of tolerance (49.99 Hz and 50.01 Hz), power system operators do not need to interact with the grid. For deviations in the interval of ± 10 mHz and ± 200 mHz, the provisioned power is set linearly until 100% of the won tender is delivered. Table 11 shows typical values for a BESS providing PCP. Further insights including technical details on BESS design for APM PCP are given in Subchapter 4.6.

Table 15 - Characteristics of the APM PCP for BESS. Based on [106].

Parameter	Value	Unit
capacity	1 – 5	MWh
power	4 – 20	MW
cycles per year	400	n
DOC	flat (refer to Figure 68)	
mean SOC	middle (refer to Figure 68)	

3.10 Uninterruptable Power Supply

Using BESSs for uninterrupted power supplies (UPS) is a common application. A BESS serving as a UPS is connected to crucial grid nodes, small island grids, or off-grid systems to either buffer frequency flickers and disturbances or to provide emergency power for blackouts of several minutes to a few hours [138, 139]. Because of the current nature of the UPS system, lead-acid batteries are the primary market participant. The worldwide markets differ significantly concerning UPS systems. The European electricity grid and the UCTE area show downtimes or grid failure times of less than an hour per year. When translated into BESS behavior, such a system shows the highest SOCs during its lifetime with a few flat cycles per year. Therefore, they are equipped and outlined by relatively cheap lead-acid BESS systems [138, 139]. Table 16 shows typical values for a BESS providing UPS. Capacity and power data based on a benchmark system by the company MTU Onsite Energy GmbH [106].

Table 16 - Characteristics of the APM UPS for BESS. Based on [106].

Parameter	Value	Unit
capacity	0.05 – 1.65	MWh
power	0.05 – 1.65	MW
cycles per year	2 [114]	n
DOC	flat	
mean SOC	high	

4 Experimental and Case Studies

The following material represents a set of case studies that have been analyzed and partially published alongside this thesis and either authored or co-authored by the author. The Subchapters 4.1 to 4.7 will summarize the different APMs for LIB BESSs and present either their legal or technical hurdles. The statements and findings are based on experiments and studies that were conducted under a simulation framework for the **Sim**ulation for **S**tationary **E**nergy **S**torage (SimSES).

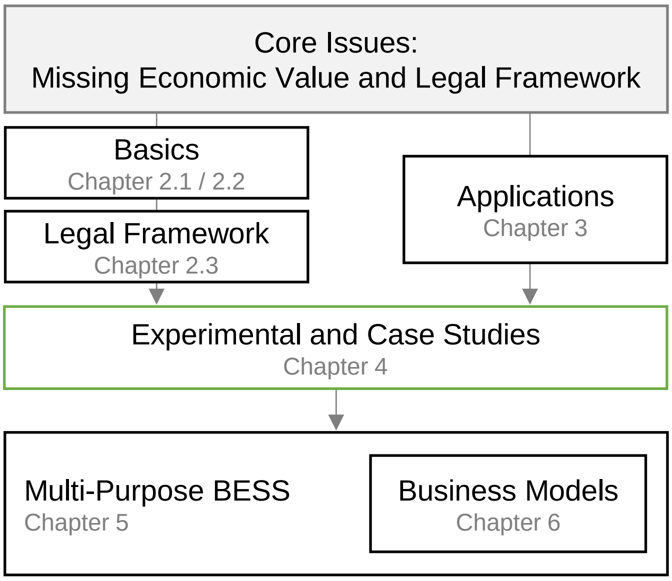

Figure 22 – Work progress in Chapter 4.

One core issue of this thesis, showing a novel system topology for economically valuable LIB BESSs in grids, requires an understanding of the existing concepts for BESSs to assess the overall system functionality, behavior and marketability. Thus, the following chapter presents the fundamentals of the integration, operation and economic marketability of some of the main BESS concepts as of 06/2016.

The excursus shows the extent to which R&D activities related to the LIB BESS module and system technology research are present in regions of Europe, America and Asia by analyzing patent, scientific and project data for LIB BESSs worldwide. R&D activity worldwide in the LIB sector has increased dramatically throughout science, industry, and field projects. Subchapter 4.2, the second excursus of this work, explains the fundamental simulation environment under which auspices the case studies 4.4 and 4.5 were developed. The SimSES simulation environment is a software program written in MATLAB that provides a framework for simulating LIB BESSs. Subchapters 4.3 to 4.7 each represent a case study for a specific APM of LIB BESSs. These include residential home storage systems, which represent the unit of a single household, an installed rooftop PV system and a LIB BESS. Subchapter 4.4 will show these systems in detail and explain the operation strategies, which have also been discussed previously in the literature. Next, LIB BESSs in an apartment building or multi-family houses are addressed; these represent another viable solution for integrating RETs and accelerating the energy transition. A multi-family environment describes the unit of a single house that is inhabited by at least two tenants. These may legally own a shared house community, the property and its assets, i.e., a PV system or LIB BESS, but a third-party owned estate can be a common entity as well. LIB BESSs in this instance will have a different operational strategy and integration both legally and technologically. Subchapter 4.5 will give a brief overview of the technical requirements and a more comprehensive view of the legal requirements. Subchapter 4.6 introduces LIB BESSs providing PCP as a centralized large LIB BESS in an MV grid. Subchapters 3.7 and 3.2 provide specific knowledge in terms of the legal and regulatory framework. Therefore, the case study mainly focuses on the operation of such a system. As a result of a case study and the modeling of a South-East-Asian island and its power flows, LIB BESSs are put into context for the possible reduction of CO_2 levels, and a lower capital cost relative to the Association of Southeast Asian Nations (ASEAN) outlined energy roadmap for this application in Subchapter 4.7. Last, Subchapter 4.8 will conclude Chapter 4 and outline Chapter 5.

4.1 Excursus: Monitoring Innovation in Battery Storage Systems Technology

In the following subchapter, the results from innovation monitoring of BESSs, specifically LIB technology, in patents, papers and projects are presented.

LIB technology has undergone a vast increase in attention worldwide from both the scientific community and the public. While portable devices are generally equipped with a highly developed battery, the need for better LIBs is a trend of the past decade. Mobile phones, smartphones, tablets, laptops, wearables, electromobility devices and the need for grid stability are the driving forces for the increase in research and media attention [45]. Because of their favorable application in a broad variety of scenarios, BESSs are a promising technology to solve major problems and advance technological progress in the near future. While general technical improvements, e.g., higher safety or higher energy capacities for LIBs, are important, the reduction of production costs is the main focus.

By reviewing patent applications, scientific papers and projects, interconnections among research, development and the market impact of BESS development can be drawn. Scientific papers provide a sufficient overview of research activity, and such a metric mostly covers publicly financed research. However, scientific abstracts, in general, are not indicative of industry research. Therefore, patent applications are used to determine industry R&D activities. (Note that patents do not guarantee successful product entry into the market.) By combining scientific data and patent data, the most promising technology developments can be determined, and the efficiency and substance of previously mentioned work can be obtained. According to the analysis of data from the worldwide patent database, PATSTAT [140], the major scientific abstract database, SCOPUS [141], and the most complete project overview on BESSs in the field, the DOE DATABASE [43], the distribution of research and the quality of LIB BESSs differ widely in various continents and countries. Overall, the research shows a major increase in activities regarding battery systems and module technology. The diffusion of intermittent RETs reveals the lack of appropriate decentralized SES solutions for grid support and other applications. The effects of intermittent energy sources start to become visible on a national scale for countries with a high penetration of RETs. While increasingly frequent periods of negative electricity prices, caused by temporary oversupplies [142], may seem bizarre, they underline the importance of SES to prevent electricity shortages, which could jeopardize the grid stability. Because of their suitability for the desired decentralized structure, EES possibilities have been analyzed in several studies, and all of the studies have highlighted the need for improvements in the relevant techno-economic parameters of such (as of 08/2016). An analysis of the PATSTAT database is an appropriate method to measure the innovation of BESS in the industrial sector by analyzing the differences in patents per country and patent family size[16] to estimate the patent quality. Other methods are shown in [144], e.g., a country-wide comparison of R&D expenditures, seem to lack precision, and input data are challenging to retrieve in sufficient quality and quantity. Therefore, PATSTAT's autumn 2015 edition, with a catalog of 67 million patent applications from more than 100 countries, represents the most comprehensive source for the outlined analyses. Submitting a search query in such a database requires a fundamental knowledge of the structure and overall configuration. There have been several approaches to working with PATSTAT, and two approaches will be described briefly. First, a keyword analysis represents a standardized keyword-based analysis, which is not suitable since the patents are often machine-translated and the data precision is not country-wide [145]. The Cooperative Patent Classification System (CPC) [17] harmonizes and refines patents to technology classes containing 250,000 subdivisions [147].

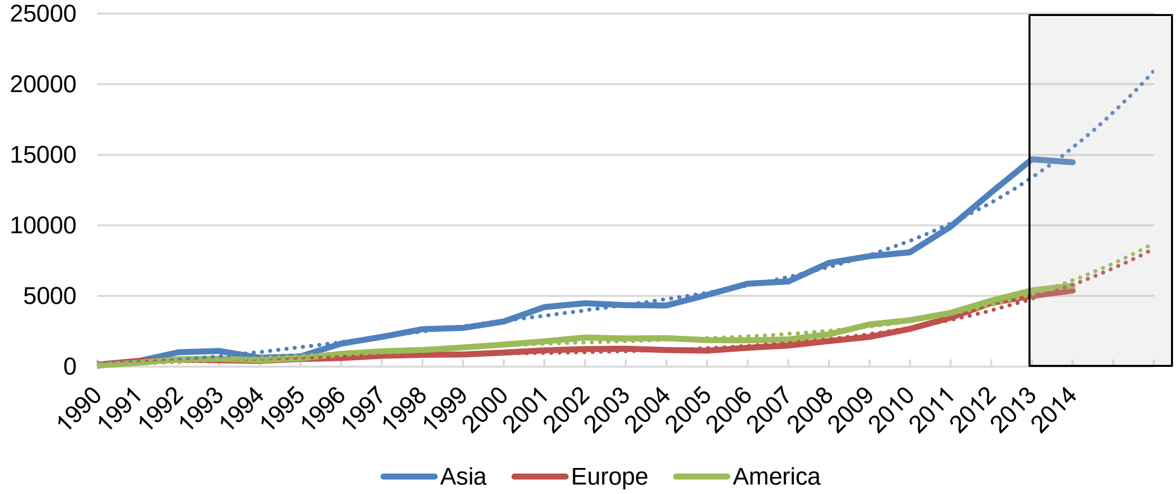

Figure 23 – Total patents in PATSTAT for battery system technology components from 1990 until 2014 for CPC classes H01M, H02J, H02H, B60, Y02 and subclasses (n = 262,075). The gray area represents vague data due to a lack of topicality in the sources.

Following the approach of [45], the CPC for BESS was analyzed and submitted to the PATSTAT database for analysis; Appendix A.1 provides the complete CPC query; however broadened by adding SCOPUS and DOE data as well as focusing on a different technology to estimate. Similar

[16] A patent family is a set of either patent applications or publications taken in multiple countries to protect a single invention by a common inventor(s) and then patented in more than one country. A first application is made in one country – the priority – and is then extended to other offices [143].

[17] The Cooperative Patent Classification (CPC) was initiated as a joint partnership between the USPTO and the EPO in which the Offices have agreed to harmonize their existing classification systems (ECLA and USPC, respectively) and migrate toward a common classification scheme [146].

to [45], the specific results for BESS and module technology, depicted in Figure 23, show the highest increase in patent applications in Asia. Since 1992, Asia has filed the most patents in the research CPC sectors. In 1995 1,876 patents were filed, and the number of patents filed has increased at a rate of 14.8% per year and reached 25,657 patents in 2014. Europe and America show only small differences; other continents do not show significant action in BESS-related patent applications. Overall, an increase in patent applications can be measured and identified, which supports the assumption that BESS technology is gaining worldwide attention. Remarkably, Asian countries have filed more patents in the analyzed areas than America and Europe combined since 1996. Monitoring the innovation in LIB BESS modules and system technology cannot singularly relate to patent filings. Patents are likely to reflect technological rather than scientific activities [148], and monitoring worldwide innovation requires analysis of scientific publishing. To qualify PATSTAT data, similar queries were run in the SCOPUS database using the database's API sockets. SCOPUS reflects the most comprehensive abstract database listing of scientific journals, books and conference papers; patent listings were disabled to avoid doublets. SCOPUS' database is best queried with a keyword search in specific categories. Thus, "battery system," "battery module" and "battery pack" were inserted as keyword search strings in the categories of engineering, energy, computer sciences, environmental sciences, and mathematics. The full search string is available in Appendix A.2. From the SCOPUS data, which is depicted in Figure 24, an increase in the number of scientific abstracts from 1995 to 2014 at a rate of 12.3% per year was identified. Additionally, comparable to the PATSTAT data, the number of scientific abstract publications from Asia increased nine-fold since 1990; Europe had more total publications than North America in 2013. Asia led in publishing scientific abstracts from 2005 onwards. Adding to the aforementioned findings, the SCOPUS data indicates a strong increase in research related to BESS systems and module technologies. Both the PATSTAT and SCOPUS analyses of patent and scientific data reflect the pure output in numbers measured on a yearly basis.

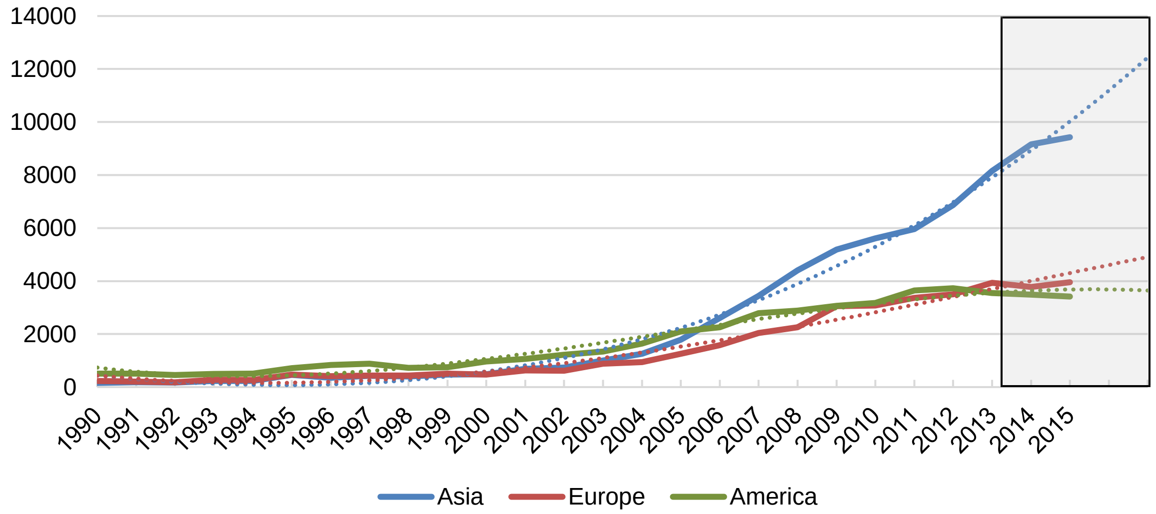

Figure 24 – Number of total scientific abstracts in the SCOPUS database for battery system technology from 1990 until 2014 for Asia, Europe, and America (n = 166,932). The grey area represents vague data due to the lack of topicality in the sources.

A more fundamental understanding of the matter is achieved by putting the total output numbers in context. Patents, i.e., the PATSTAT data, can be categorized and qualified by adding metadata to the analyses, e.g., geographical patent family size or total forward citations [149]. Monitoring the innovation for BESS technology worldwide must cover metadata analyses because several countries worldwide file numerous patents that will never be actionable [150]. A patent's family size is described by the OECD as "*the set of patents filed in several countries which are related to each other by one or several common priority filings* [..]" [151]; a priority filing is the first patent published within a patent family. A patent's geographical family size counts the number of jurisdictions identified in a patent family.

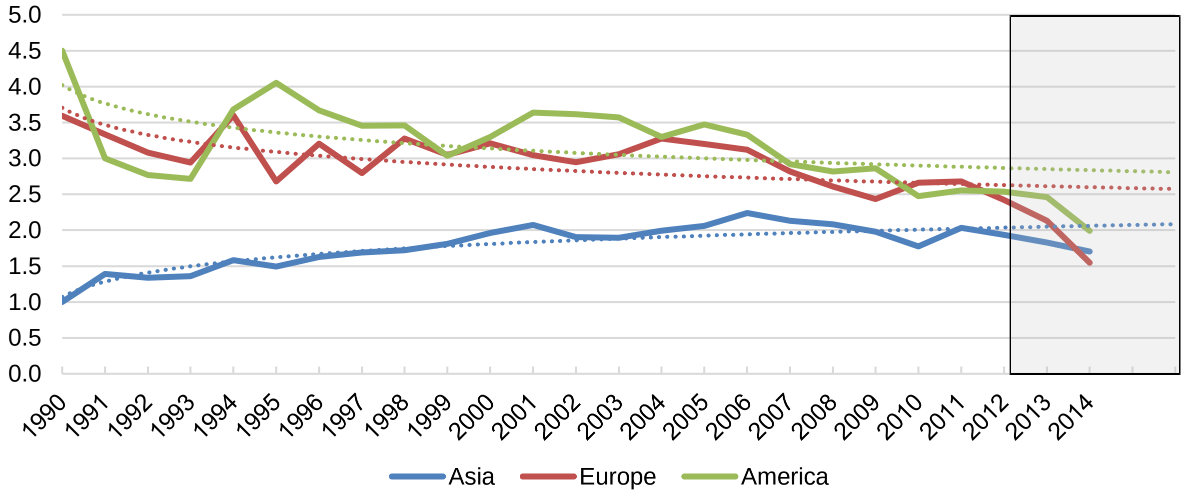

Figure 25 – Geographical family size index for Asia, Europe, and America qualifying PATSTAT data of the searched CPC classes (n = 262,075). The grey area represents vague data due to the lack of topicality in the sources.

Forward citations can be defined as "*the number of citations a given patent receives*" [151]. According to this measure, a patent is more valuable for every additional country in which it has been filed [152]. In addition, the geographical family size can be used to evaluate the innovativeness of countries [149]. Thus, the division of the geographical family size by the total numbers of patents filed per country per year is introduced as the geographical family size index, which represents the quality of the total patent output. Figure 25 depicts the geographical family size index for Asia, Europe, and America. The findings in Figure 25 show that the overall quality of patents filed by America is greater than those of Europe and Asia. However, the trend of Asian patents increasing steadily in quality stands in contrast to a number of patents filed by Asia, as shown in Figure 23; Asia shows a major increase in patent filing, but the overall quality of the patents has increased more slowly. Furthermore, the usage of forward citations highlights that patents of more technological importance [153] lead to more innovative output [154] and are more valuable [150]. Thus, the average number of citations per patent provides an economic and technological quality index. Figure 26 depicts the technological and economic quality of the patent data measuring the total average forward citations, and Figure 27 depicts the technological and economic quality of the SCOPUS data measuring the total average forward citations. The trends show an overall decline in the estimated patent quality, which can probably be linked to the overall number of patents decreasing the amount of possible citations per patent based on the overall numbers of patents available.

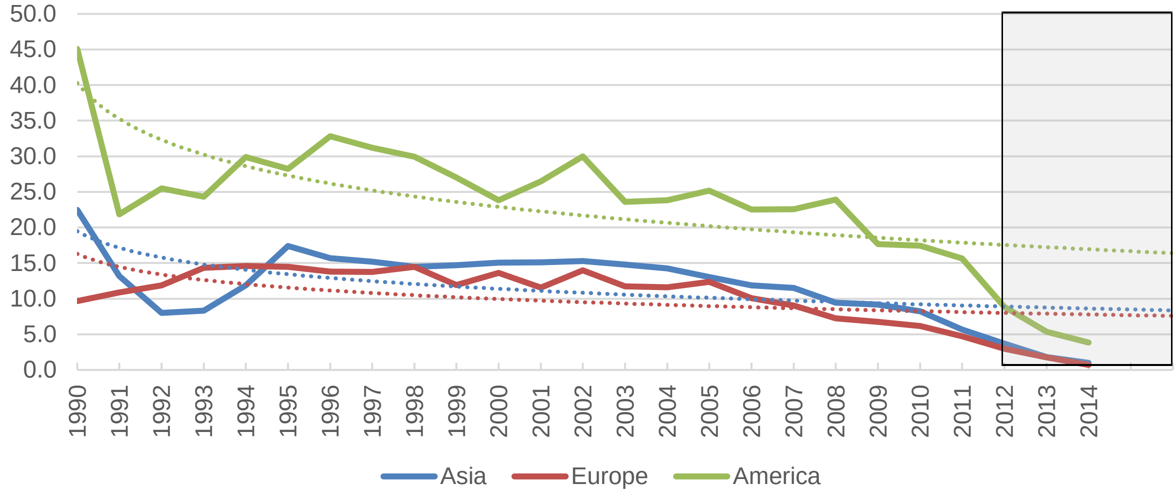

Figure 26 – Average number of forward citations for Asia, Europe, and America qualifying PATSTAT data of the searched CPC classes (n = 262,075). The grey area represents vague data due to the lack of topicality in the sources.

However, the average patent quality in America is significantly higher than Asia's and Europe's. Data for 2012 and the following years show a major decrease in the calculated quality, which is based on the fact that an average patent needs time to be recognized and cited. Similar to the PATSTAT findings, the analyses of SCOPUS scientific data show an overall decline in forward citations per scientific publication see Figure 27. However, in contrast to the PATSTAT data, Asia shows a major increase in forward citations of scientific literature per publication since 2005 in the selected field of BESS technology. However, it is unclear which other science fields the majority of citations are derived from and how this effect can be measured. A preferred measurement tool is the h-index, which was initially proposed by Hirsch in 2005 [155]. The h-index defines an index of h that measures an author's h publications that have each been cited by other sources h times. However, the h-index does not measure trending topics, i.e., newly relevant literature that is more valuable than outdated topics with vast citations.

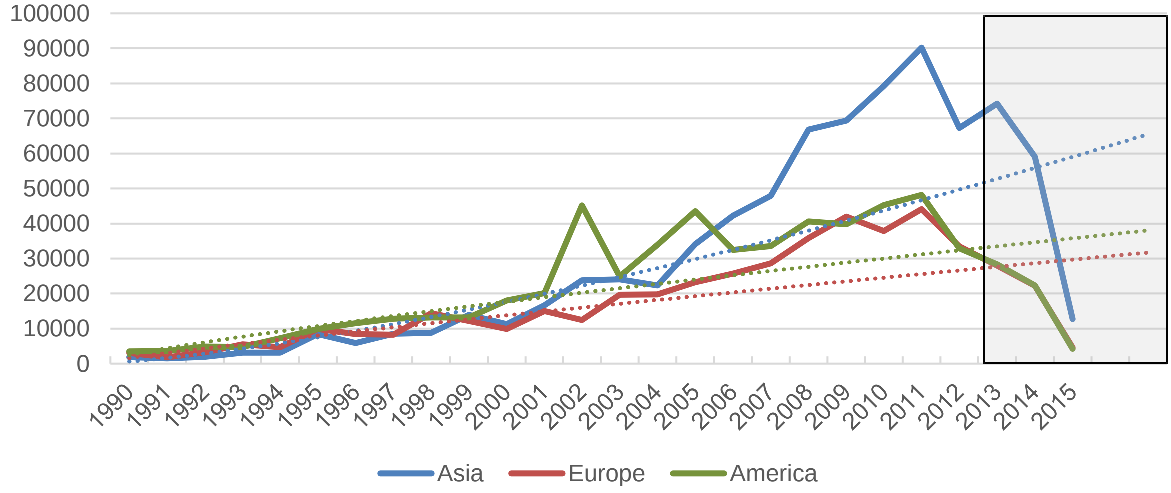

Figure 27 – Total number of forward citations for Asia, Europe, and America qualifying SCOPUS data from the sourced keyword search (n = 166,932). The grey area represents vague data due to the lack of topicality in the sources.

To overcome these shortcomings, [156] created the average contemporary h-index (ACH) in 2007, which is able to disclose latent facts in citation networks, i.e., trendsetters and brilliant young scientists, i.e. papers in SCOPUS, and avoid overrating outdated work.

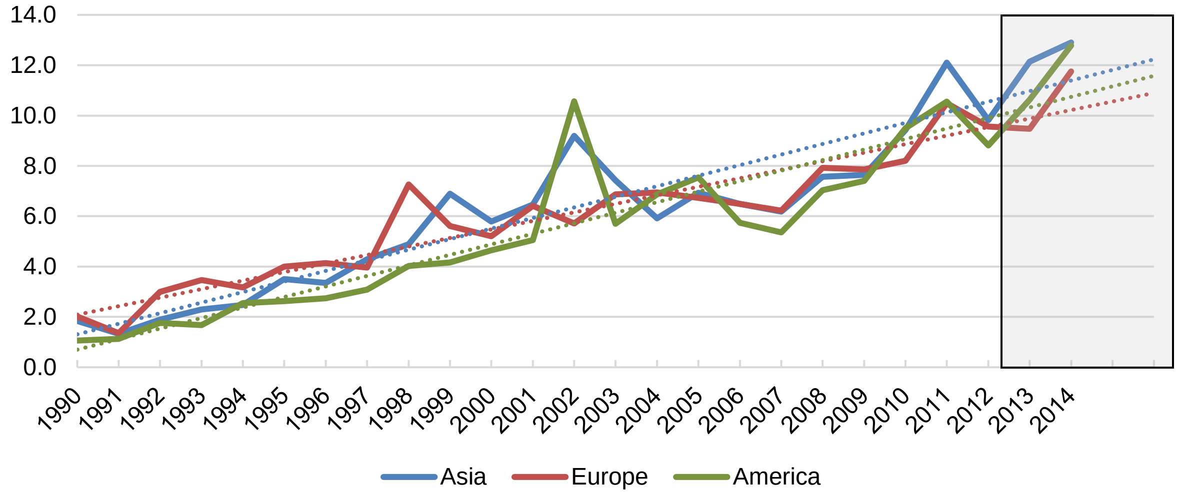

Figure 28 – Average contemporary h-index [156] for Asia, Europe, and America qualifying SCOPUS data from the sourced keyword search (n = 166,932). The grey area represents vague data due to the lack of topicality in the sources.

An analysis using the average contemporary h-index of the SCOPUS data shows that the ACH-index, which is depicted in Figure 28, does not significantly differ and does not show any significant trends for the analyzed continents. Thus, the SCOPUS data are of limited use for monitoring BESS technology innovation for quality differentiation.

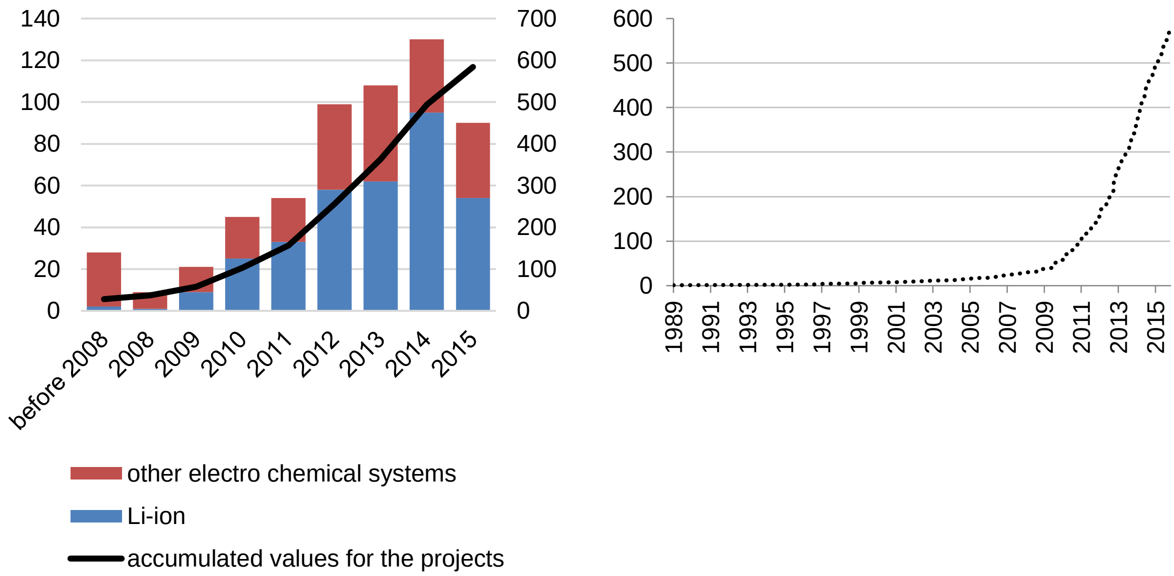

Figure 29 – Left, the annual and cumulated number of electrochemical storage systems data derived from the DEO Database (n = 585); right, the number of electrochemical storage systems projects.

In addition to technological and scientific data analyses, innovation monitoring for BESS technology can leverage from the DOE Global Energy Storage Database [43], which is maintained by Sandia National Laboratories. The DOE Global Energy Storage Database was introduced by the U.S. Department of Energy and Sandia National Laboratory in 2012 with two major purposes: to contribute to the rapid development of BESSs and to provide free, up-to-date information on grid-connected energy storage projects [43].With a total number of n_{total} = 1,370 records, taken out of the DOE database, distributed over all types of SESs, electrochemical systems account for up to 55% of the entire dataset. Within the range of electrochemical energy storage, the LIB-based systems have a share of 60%, which corresponds to 33% of all projects. The evaluation of the DOE data reveals that most BESS projects focus on the following applications: 1. renewable capacity firming, 2. frequency regulation and 3. electric bill management. Renewable capacity firming describes any application separating the generation of RETs and their distribution, and electric bill management refers to the use of BESSs to achieve lower electricity costs, e.g., by storing RET surplus energy. Based on all of the analyzed applications, 75% of LIB BESSs have a capacity of less than or equal to 1,000 kWh, and 50% of LIB BESSs have a capacity that is less than or equal to 200 kWh. Figure 29 shows the resulting share of LIB BESSs from 2008 until 2014 with a yearly increase of 47% in LIB BESS projects. Also depicted in the right part of the figure is the steep increase in BESS projects. Further data are available in the Appendices A.3 to A.5. In conclusion, the outlined analyses of the R&D activity for LIB BESS module and system technology in patents, science, and projects agree with the vast impacts for policy makers. From a scientific point of view, a clear dominance in R&D activity can be observed in the Asian region, depicted in Figure 23 and Figure 24. This is, however, relativized when interconnecting the data, i.e., indices or other metrics such as the h-index or ACH, to estimate the quality of the R&D activities. Figure 25 to Figure 28 reveal these interconnections and indicate that the sheer amount of R&D activity in the Asian regions is, relative to the overall size, similar to that in America and Europe when factoring in the quality of such work. Figure 28 shows that in 2006 and 2007, the existing "*skeptics towards LIB technology due to product recall campaigns in 2006*" [45] were overcome, and the overall R&D activity increased, which was found by [45] for SES technology as well.

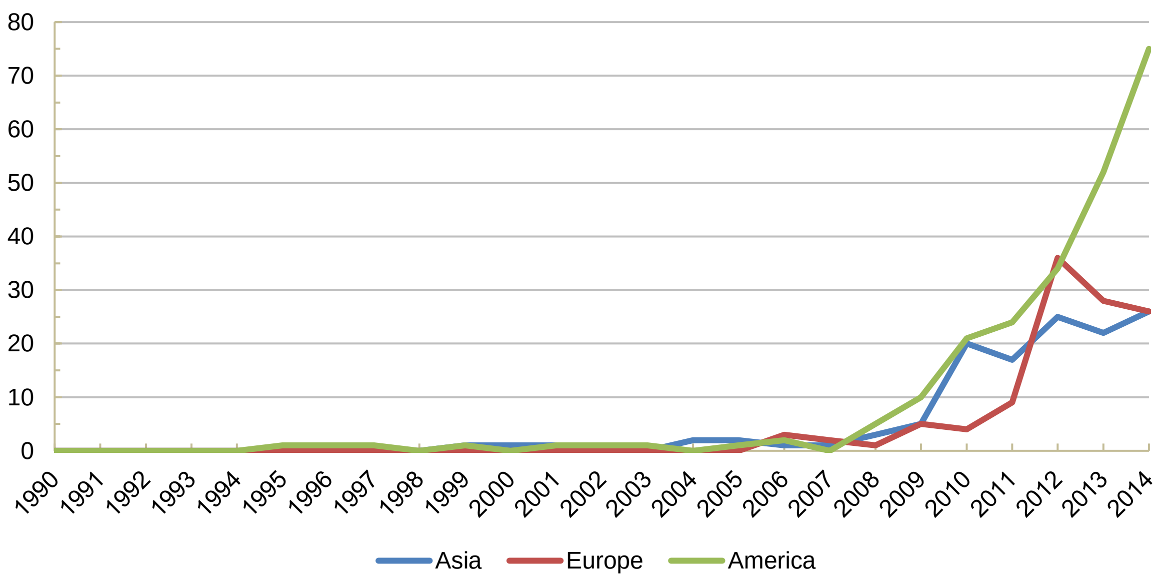

Figure 30 – Number of electrochemical energy storage projects per year.

While patent and scientific based data show similar tendencies for both, the overall quantity and quality for all analyzed areas and the overall project implementations worldwide indicate a different view. While America, Europe, and Asia started large LIB BESS project installations simultaneously beginning in 2010, the continent of America, especially the U.S., almost doubled their LIB BESS projects by late 2014, refer to Figure 30. Recent roll-outs of LIB BESSs under competitive market processes, i.e. Tesla’s win of a 20 MW / 80 MWh LIB BESS request for proposal as of 09/2016 [157], brought in context with the aforementioned resulting timeframes of increased activity in research, papers and projects, from SCOPUS, PATSTAT and DOE data, leads to the assumption that it takes a continent, or country, between three to six years from R&D in science and industry to implement demonstrator systems and another four to eight years to move from demonstration projects to economic, i.e. self-sustained business cases. This timing can be especially important for further analyses regarding the specific timelines for R&D funding, legal and regulatory action, and market building competitiveness for LIB systems, empowering these to win open requests for proposal tenders and other markets.

4.2 Excursus: The Simulation Environment – SimSES

The software SimSES allows for a detailed techno-economic simulation and evaluation of SESs with a current, main focus on LIB BESSs. Various application scenarios of SESs, such as self-consumption maximization in households with PV systems, grid-supporting operation via peak load reduction, provision of control reserve, arbitrage trading on the electricity market, or even the combination of different applications, can be simulated. The simulation scenarios and the technical components of the SES can be flexibly selected. The abstract energy storage model of the modular and object-oriented software is one of the most important components, which allows for the variation of different storage technologies. Furthermore, stress detection facilitates the estimation of the degradation of the energy storage device. For this purpose, various aging models can be used. However, detailed models are specifically developed for BESSs based on aging experiments. To optimize the use of the EES in various applications, a large number of operating strategies are implemented. In addition to the technical analysis for the calculation of relevant key figures, an economic evaluation allows for an economic investigation of the simulation results. The simulation tool SimSES has already been used in various publications for the analysis of the application of "PV home energy storage" [26, 158] as well as "primary control reserve" [137] and is currently being further developed. The medium-term objective is to make the software available for further non-commercial use and development to the public. The software is developed in MATLAB and Simulink in conjunction with vast amounts of experimental data from LIB cell and LIB module testing. The founding developers are researchers from the Institute for Electrical Energy Storage at the Technical University of Munich; who presented the simulation framework in several contributions to the scientific community [159–162]. Figure 31 depicts a general overview of the SimSES software and its available modules for BESS simulation. As of 12/2016 the SimSES tool is comprised of the following modules and models

- the operation strategies and applications module
- the electric model
- the thermal model
- the battery voltage-resistance model
- the aging model

- the economic valuation module

each of which contains at least one but often several options to carry out simulation tasks according to the simulation environment the storage is set up for. The tool handles simulation data in a single storage objects which can be called by functions of the different modules and models according to a main script. The main script in SimSES is arranged as a series of functions, which handle one or more BESS objects, to conduct the simulation over time and delivering visual and data results. In this thesis, the operation strategy module, the operation module, the electric model and the aging model were used. The thermal module and the battery voltage-resistance model were not used because of simulation time and the necessary precision that the hypothesis of this work required.

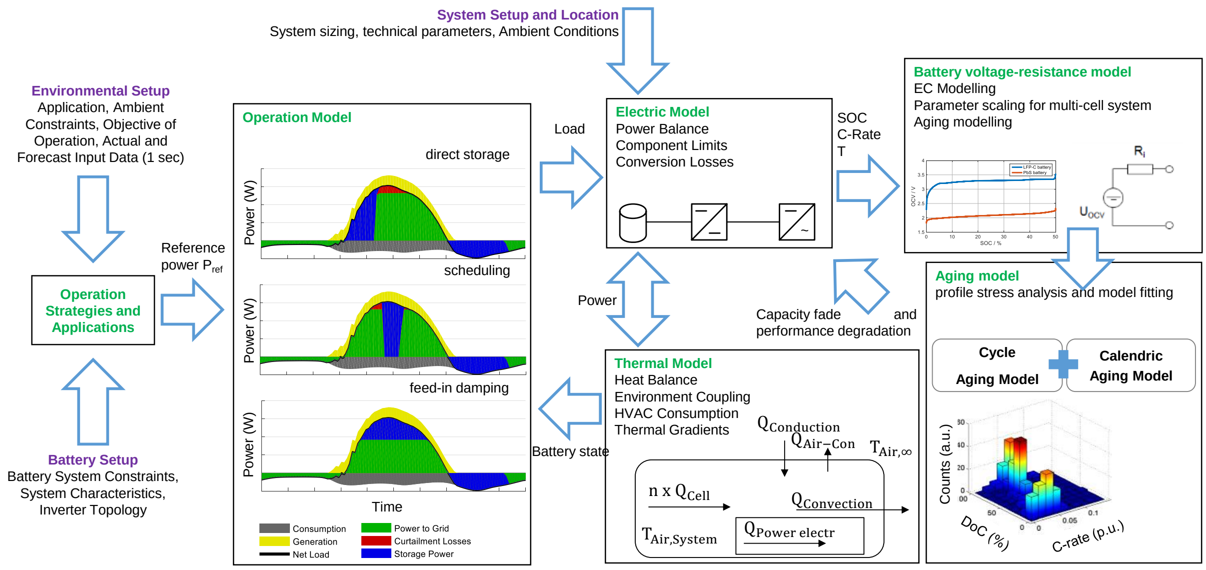

Figure 31 – The SimSES software with a depiction of all the available modules for BESS simulation as of 11/2016.

For a better overview, the following will discuss how SimSES works internally, what the input data is and how the results are evaluated.

The basic input data for the SimSES software consist of a series of data profiles, e.g. a load profile for the grid the BESS is simulated in or a PV profile for generation data, as well as definitions to set up the simulation object. Besides, helping variables and simulation parameters, e.g. starting time of the simulation, end time of the simulation, length of the input load profile et cetera, the input data covers the setup of

- the PV system/s attached to the BESS
- the type of thermal model
- the type and settings of power electronics (including efficiency formulas)
- the technical data for LIB
- the economic data for valuation calculations
- the operational strategy of the BESS

The following will briefly discuss the general functionality and logical code structure of the SimSES tool and has been published in “Economics of Residential Photovoltaic Battery Systems in Germany - The Case of Tesla’s Powerwall” [158].

The SimSES computes the power flow between solar generation, a household load, BESS and the public electricity grid, considering inverter efficiency and battery round-trip efficiency as well as the aging related capacity fade of storage. The sample time (Δt) between the simulation steps (k) is variable, however limited to the quality of load and generation profiles. The simulation is run for the whole regarded period to explicitly capture the effect of battery degradation on the system performance and consequently the generated savings. The power values are calculated in watts, energies are considered in watt-seconds, the SOC and efficiencies are calculated in per unit values between 0 and 1. Self-discharge of LIB typically ranges around a few percent per month [163] and is thus neglected in calculations. The battery energy capacity does not remain constant, but continuously decreases over time because of aging effects.

```
main script start

load generation data
load load data
set helping variables
set simulation parameters
set technical data
       set technical data of PV system
       set technical data of load
       set technical data of storage technology
       set technical data for thermal Model
       set technical data of power electronics
set economic data
       set economic data for electricity prices
       set economic data for BESS cost
       set economic data for inflation
create storage object
       create power electronics
       create battery
       create aging Model
       create generation
       create load
       create cost structure
       create electricity prices
       generate storage object
storage simulation
       run storage
              load operation strategy model
              execute storage operation strategy
                     calculate residual load
                     iterate power BESS
                     load electric model
                            set power BESS
                                   apply power limits
                                   calculate power at battery terminals
                                   calculate self-discharge
                                   calculate SOC
                                   update storage object
                                   detect aging stress
                                          load detection model
                                          cycle detection
                                          start cycle detection
                                          determine cycle stress
                                          update aging stress
                                          update capacity throughput
                                          update storage object
                                   calculate aging
                                          load aging model
                                          aging calendric
                                          aging cyclic
```

```
                                        calculate total aging
                                        calculate storage capacity
                                        update storage object
            calculate grid power exchange
            limit power to grid
        evaluation of technical data
            calculate total energy
            calculate total grid interaction
            calculate peak loads
            calculate losses
            calculate SCR
            calculate SSR
            calculate reference scenario without storage
            calculate aging values
            update storage object
        evaluation of economic data
            calculate interest rates
            calculate depreciation times
            calculate total investment
            calculate replacement cost
            calculate maintenance cost
            calculate energy cost and revenue
            calculate NPV
            calculate reference scenario without storage
            update storage object
        save storage object
main script end
```

Figure 32 – Basic structural overview of the SimSES tool, laying out main functions and calculations necessary for simulation.

The battery aging model adjusts the capacity of the simulated residential BESS continuously with respect to simulation time passed and the battery's load. Efficiency degradation is not included in the aging model. A cycle-counting approach is used to determine the stress put on the battery. This method stems from the materials science, where material fatigue is defined as the weakening of material due to repeatedly applied mechanical stress. Experimentally gained Wöhler-curves (also referred to as S/N-curves) describe the amount of stress cycles related to the applied force onto the material, until it fails. This method is adapted to estimate cycle aging of batteries. Assuming independence of calendric and cycle aging, a superposition approach to account for both simultaneous aging effects is used. Cyclization-caused degradation depends only on the inflicted stress on the battery; the aging progress itself does not influence the aging speed, hence time-dependency is neglected in the system simulation. The depth of cycle (DOC) describes the amplitude between the peak and the minimum state-of-charge within a cycle and determines the cycle-aging. The cycle counting algorithm detects half-cycles. These are distinguished between charging, discharging, and resting periods of the batteries. The cycle counter determines the cycles by detecting zero-crossing of the battery terminal power-flow. Every time the power-flow changes to zero, the end of a half-cycle is declared and the difference of the SOC at the beginning and at the end of the detected cycle is calculated in order to obtain the DOC. According to a model provided by [164], smaller DOCs lead to reduced aging when compared to large DOCs.

Thus, the SimSES tool provides a comprehensive simulation model for a single BESS operating a specific OS for a given generation and load profile. By combining several SimSES simulations and overlaying analyses and manipulation functions for load and generation of each single simulation, multi-purpose BESS can be simulated. Refer to subchapter 5.2 for a full description of an MP-BESS simulation setup based on SimSES.

4.3 Case Study: Grid-Level Adaptability for Stationary BESSs

Regarding the aim of economic implementation of BESSs, understanding and predictability of the usability of BESSs are prerequisites to assess the overall system technologies, costs and economic benefit. Thus, the ability of assessing the adaptability of BESSs in a certain grid level is directly linked to the decision to invest. The fundamentals of grid-level adaptability required for such challenging predictions are presented in Chapter 4.1 and are published as the "Evaluation of Grid-Level Adaptability for Stationary Battery Energy Storage System Applications in Europe" [39].

Fundamentally, BESS implementation is dependent on the readiness, i.e., the economic value, of a certain APM for a specific grid level. For a BESS, the highest economic value is expected in the grid level in which its adaptability, e.g., suitable regulatory framework or working business case, is the highest. In addition, MP-BESSs, which will be further described in Chapter 5, have yet to be analyzed for possible grid implementation according to the APM necessary voltage level, since these systems serve grid overlapping.

The vast majority of BESS implementation theories and investigations focus on a single grid level, whereas the interaction of such systems between grid voltage levels has been widely neglected [165]. Whereas the necessity for SES in future grids seems unavoidable, policymakers, projectors and operators of BESSs focused only recently (as of 08/2016) on stacking of APMs to increase BESSs' economic value.

Complications and challenges in transmission and distribution grids originate mostly from the sum of challenges in lower voltage grids. BESSs are a major factor in addressing these challenges at their origin and influence grid stability and quality in a positive way. The superimposed effects from several LV-implemented BESSs on higher grid levels and their multiplicative positive effects on upper grid levels are described in this chapter. Figure 33 depicts the effects of Europe's energy transition toward a low-carbon future over time. The electricity is produced hierarchically and fed into the XHV or HV level before it is transported to lower voltage levels to be transformed into MV and LV levels to be consumed locally. The European electricity grid is divided into four different voltage levels: XHV, HV, MV and LV with a maximum of 380 kV, 110/220 kV, 10/20 kV, and 400 V, respectively.

The shift has already occurred from a typical unidirectional load system, in which power and energy flow mainly from large, central power plants and are transported from extra-high voltage (XHV) levels into lower grid levels and finally to the end consumers, to a bi-directional grid with load flow over all voltage levels. In several grid areas in Europe, peak load flows in backfeeding scenarios have already reached medium-voltage (MV) and even high-voltage (HV) grid levels. These areas face shifting in load flow due to massive installations of RETs. Whenever local RETs feed-in more energy and power than the demand, backfeeding occurs. It has been observed in several areas in Bavaria, Germany that massive RET installations in LV grids lead to backfeeding into MV and HV areas. Two effects categorize this as a problem. First, the large backfeeding energy and power have to be consumed somewhere else in the grid. If this is not possible, grid operators will activate control structures, i.e., demand-side management, and negative energy prices will occur in electricity markets [166–168]. Second, the energy that has been produced in a local grid area has the greatest carbon-reducing effect if it can be consumed in an intelligent way directly in the local grid area.

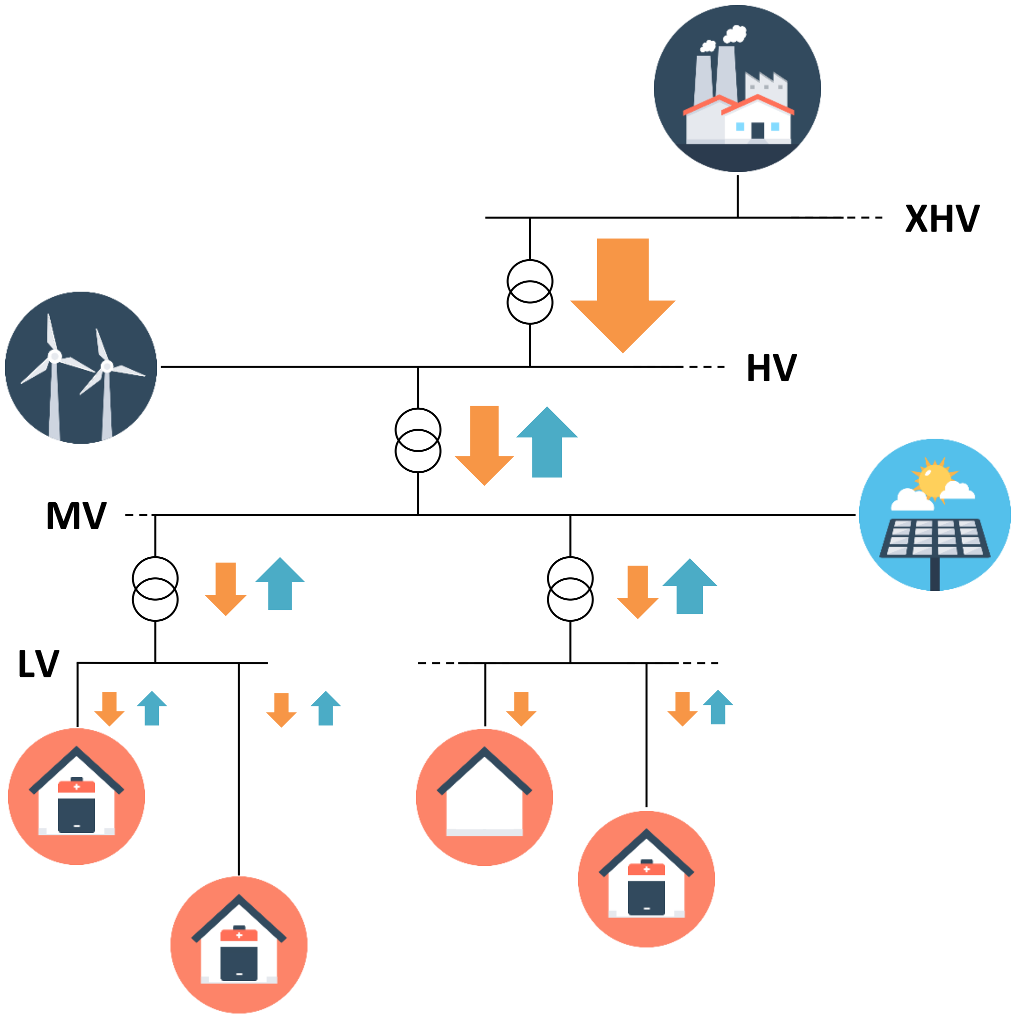

Figure 33 – Grid structure and influence from heavy installation of renewable-energy producers, mainly decentralized producers at the distribution grid level. Blue arrows show backfeeding of power up to the XHV grid level due to the heavy PV penetration in the LV and MV grids. Orange arrows show the conventional power flow from the XHV toward the consumers without a backfeeding scenario [39].

However, the vast majority of power peaks occur over only a few hours [166] in a year. [169] shows that the top 1% of power peak hours in a year (87 hours) accounted for 8% of annual grid reinforcement spending (680 million USD) and that the top 10% of power peak hours in a year account for 40% of the annual grid reinforcement spending (3 billion USD). Similar findings are presented in subchapter 4.3 for a case study in Germany.

Unusual days, i.e., a Sunday during holiday time in May with comparably cold PV systems, minimal grid load in Germany, and major feed-in from RETs, lead to such events. Consequently, grid level adaptability includes the ability of a BESS to prevent such errors in the grid by providing negative or positive power to the grid. A better understanding into the matter is achieved by examining the history of grid expansion and configuration in Europe. Over the last century, grids were developed mainly by state-owned utility companies to secure economic growth and wealth for the people. Several voltage levels with different purposes exist between the production of energy and the consumption of energy, and the choice of grid level connections needs to consider transmission losses and the ease-of-handling; longer transmission distances require higher voltage levels because losses along the line are proportionally smaller for higher voltage levels. However, this approach leads to an increased insulation requirement, which is accompanied by handling issues and a cost increase. Distribution grids in local areas are different from transmission grids and do not require long distances between points of interest; thus, they consist mainly of LV grid levels.

The XHV grid level in Europe serves as a transmission grid over long distances within and between national grids. It operates at a voltage of 380/220 kV, and connected electricity plants are rated at up to several 1,000 MVA. At this level, the grid is required to be operable even after one component, such as a transformer or a circuit, fails (i.e., the n-1 criterion). The HV level in Europe has a rated voltage of 110/60 kV and serves the trans-regional transmission of electricity. Typical electricity plants in this grid level yield powers of several MVA up to several 100 MVA. The n-1 criterion is also in effect at this level. Only a small share of the HV grid is built using cable (9.5%), and the remaining majority of the grid consists of overhead lines. The regional distribution of electricity is performed with MV grids, and typical consumers yield larger power loads of more than 100 kVA. The voltage level ranges from 3 kV to 30 kV. Most lines at this level are installed as cable (78.8% in Germany). Small scale prosumers (prosumer: a consumer who becomes involved with generating, using and providing electricity for their own needs) are connected to the power system in LV grids. This scale involves private and commercial customers using less than 100 kVA. Cable installation is dominant at this grid level, with a share of 89% in Germany. The n-1 criterion is frequently not in place, and the additional investment cost to ensure the enhanced reliability is not justified for small grid sizes with only minor impacts of power outages.

Currently, an increasing share of RETs results in an increasing number of grid errors and quality problems. Transmission congestion, balancing needs, voltage limit violations and overload scenarios of network operating resources are some of the challenges induced by RETs. It has been shown in [39] the extent to which BESSs adapt in the different grid levels in Europe. Table 17 shows the technical grid level readiness for different BESSs regarding the influence on other grid levels when inserted in a specific grid level with a certain APM. Because (as of 2016) most load peaks, mainly for a backfeeding scenario, occur in LV and MV grids, a BESS serving APM GRID, see Subchapter 3.4, is best situated near the error sources in the same grid level. Possible unloading of an MV/LV transformer is technically only possible within the LV level because of grid overloading in the LV level. Large-scale RET implementation in LV grid areas often leads to an overloading of the local grid because of highly fluctuating energy production without any reliance on the local grid load during the same time. Thus, an LV grid will start feeding energy back whenever the produced energy exceeds consumption, leading to grid and transformer overload in the worst cases. A BESS situated in the same LV grid can be charged during times of high backfeeding power and discharged during times of low or no backfeeding power to unload the local grid and transformer. A BESS situated in the superimposed MV grid cannot fulfill this task. With regard to APM SELF, see Subchapter 3.1, BESSs are rather unusual for implementation if the grid levels exceed LV since most consumers interested in SELF are situated in LV grids; in Germany, the renewable energy acts progressively subsidy BESSs in these areas. It was shown in [39] that the LV level promises the most functionality for assessing the possibilities of BESSs.

Table 17 – Evaluation of technical grid level readiness for providing a certain APM with BESSs under the constraints of BESS sizing and costs [39]. The more stars the higher is a BESS's APM in a certain grid level. Gray field show either technology or economic unviable cases.

Level / APM	XHV	HV	MV	LV	Source
GRID		*	**	***	[117, 118]
SELF				***	[158, 170–173]
PEAK-S		*	**	***	[132, 133]
UPS		*	**	***	[138, 139]
PCP	***	***	***	***	[126, 127]
SCR	*	***	***	***	
TCR		**	***	***	
ISLAND		**	***	***	[174–177]
IDM	***	***	***	***	[113]
BSC	**	***	***	***	[41, 108]

On the grid of the DSO KWH Netz

The KWH Netz GmbH is a distribution grid operator (DSO) situated 45 minutes east of Munich, Germany, and it has been one of the most valuable partners in creating this thesis, which is supported with data from their grid. The KWH Netz GmbH operates, plans and expands the electricity distribution grid for 21 municipalities with 550 transformer stations and over 15,000 grid connections and a single circular MV grid that is connected via MV/HV transformer stations to higher grid levels. The KWH Netz GmbH's service area covers 314.4 km².

The following data and analysis pertain to the complete service area of a DSO in East Bavaria. For data gathering, KWH Netz GmbH worked closely with the EEBatt project and provided deep insights and data for scientific investigations in this thesis.

With over 48.46 MW of RETs, the KWH Grid area shows significant installations of RETs, depicted in Figure 34, in the last decade. Out of the 48.46 MW, 36.9 MW of non-adjustable generation originates from PV systems installed in LV and MV grids [178]. The share of wind power in this specific region is relatively small and contributes negligibly to the outlined hypotheses and calculations. The total RETs mounted in KWH's LV grid account for over 32.06 MW [178] in power, which leads to major feed-in management actions by KWH Netz GmbH to ensure grid stability, particularly in the summer. Currently, the foremost LV and MV biogas RETs are operated automatically and can be directly controlled by KWH Netz GmbH for grid stability purposes from a central control station. The bottlenecks for grids under these circumstances are line distances and transformer capability, representing all the transformers that are in overloading status over a longer time period because of vast amounts of backfeeding power, overloading the thermal overcapacity with which transformers are equipped. Considering that 60% of RETs in the KWH's grid are installed in the LV grid, it is apparent that a decentralized solution approach to solve the upcoming problems should be preferred to alleviate grid bottlenecks. The bottlenecks, foremost situated in the LV grids because of the lower oversizing of the grid equipment, are the installed LV/MV transformers that are too small and have insufficient line capacity in the LV grid. Both bottlenecks lead to overvoltage problems and overloading problems in grid utilities.

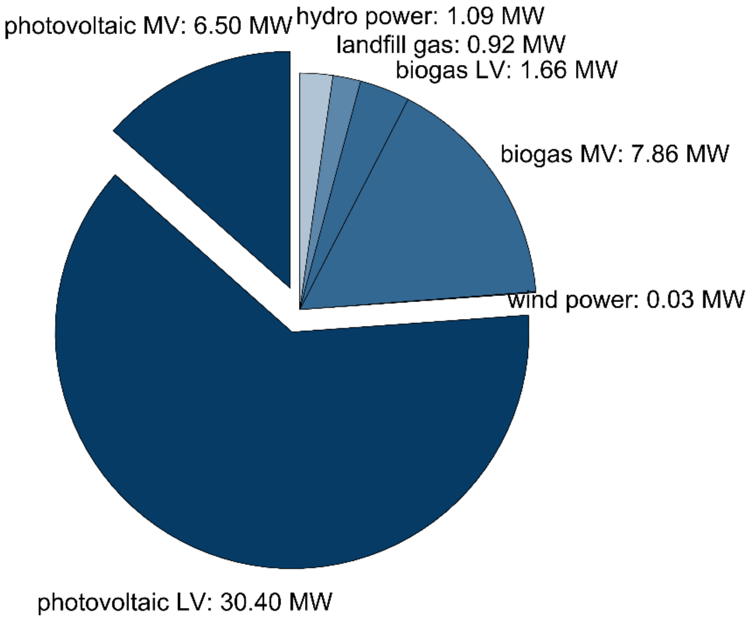

Figure 34 – Shares of renewable generation for the KWH service area [39].

This situation is the result of the quick growth of distributed or decentralized RETs that feed energy and power into the grid in combination with the underlying grid planning periods of several decades, mainly due to the average grid equipment lifetime of 30 to 40 years [179].

Extreme installation of RETs in small grid areas affects the connected MV grid and the HV/MV transformers. Figure 35 depicts the exchange of the considered MV grid with its superimposed HV grid structure for both transformer stations, Altdorf and Stollnkirchen. Over the years from 2009 to 2015, the bar plots show the exchanged energy, and the line plots refer to the maximum 15 minute measured power peak in each transformer station. Each of the aforementioned values is shown separately for the positive and negative load flow over the substation. While the maximum peak loadings for the whole period under review remain nearly constant, the maximum power fed into the HV grid from the MV grid shows a steep increase. With the knowledge that no relevant additional fossil fuel generation units have been installed in this timeframe, the rise of the maximum power backfeeding is the consequence of adding RETs to the MV grid. Data from the central RET register in Germany indicate that mainly PV in LV is the reason for this observation. Aside from the maximum backfeeding power, a decline in the overall energy consumption from the superimposed HV grid can be observed. This observation is based on the fact that with more RET installations, the amount of consumed energy directly from RETs instead of from HV grids is higher. Such a steep incline in both power and energy backfeeding led to a situation in 2015 in which energy was fed back into the HV grid for more than 77% of the operation time at Stollnkirchen substation. This result was caused by massive RET PV feed-in during the day and additional RET biogas feed-in at night. Additionally, in 2009, the maximum backfeeding for Stollnkirchen was 3.50 MW, whereas, in 2015, this number increased to 18.48 MW. Even though the increase gradient of the RET backfeeding power has declined over the past several years, a specific trend toward major power flows from MV into HV grid areas can be observed.

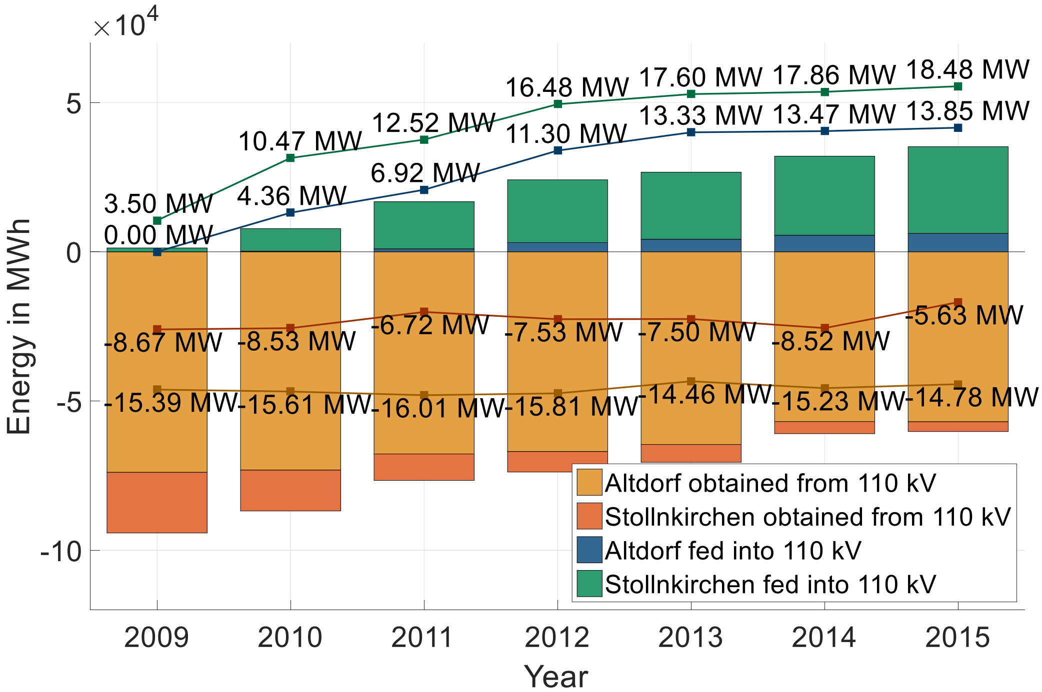

Figure 35 – Measured exchange (blocks) with the HV grid at transformer stations Stollnkirchen and Altdorf for the years 2009 to 2015 (positive values indicate backfeeding from MV to the HV grid) [39]. The lines represent the maximum measured 15-minute peak load occurring each year for each transformer station.

Based on the given results and analysis, the methods and regulations for grid expansion are not valid for a shift in the grid usage from the normal parameters. Regular grid expansion was and is triggered by load profile analyses of DSOs and TSOs to maintain grid stability and reliability. However, in the presented case, grid backfeeding outnumbers the grid load regarding the maximum power necessity. Thus, grid expansion and reinforcement must consider major feed-in peaks due to the high RET share in grid areas. With regard to the aforementioned discussion, the increasing overall share of RETs worldwide, e.g., in Germany the Renewable Energy Act (EEG) set a goal of a 50% share of RETs by 2030, will increase these problems in grid structures. Consequently, the amount of electricity fed into higher grid levels will increase in the future to meet the goals of the RET shares. Considering not only the consequences in the MV and HV grid levels, the LV transformer stations in the KWH grid area were analyzed. Additionally, BESS implementation with different setups in the studied grid were designed and analyzed. Because of the high number of RET sharing in grids, increasing values for curtailment at the generation units are necessary; otherwise, the grid overload would lead to malfunctions when network resources are overloaded for backfeeding scenarios. If this situation were to occur, individual monitored resources would reach their limits, and smaller entities without monitoring, such as MV/LV transformers, would also be overloaded. Figure 36 represents all transformer stations in the analyzed grid area, and the foremost smaller units with $S_n < 100\,kW$ (not exclusively, however) show overloading during backfeeding operations. For all of the MV underlying LV grids, decentralized solutions present a valuable option for solving local grid overloading problems and positively influencing the superimposed grid reinforcement and cost savings in the grid extension. The data shows that the presented HV/MV substation with a maximum power of $S_{th} = 17.5\ MW$ operated for 390 minutes in overload in 2015. Connecting this observation with the assumed increase in the RET share and backfeeding power, it is concluded that there is an urgent necessity for grid expansion or reinforcement at this substation.

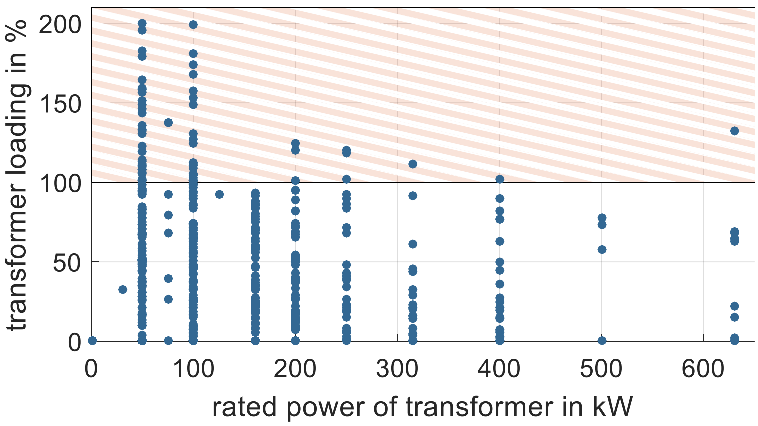

Figure 36 – MV/LV transformer loading in 2015 for the backfeeding scenario with no assured load and a simultaneity factor of 0.85 [116] for distributed generation [39]. Each data point represents a single transformer and its maximum load during a one-year simulation in the assessed grid.

To avoid, conversely, an exchange of the complete substation structures, a relief of less than 2 MW must be realized. BESSs inserted in the local LV grid and operating in the SELF APM (Subchapter 3.1 and Subchapter 3.3) can achieve a reduction at the mentioned HV/MV substations. Based on the local overloading scenarios, shown in Figure 36, the advantage of decentralized approaches becomes apparent.

Namely, an implementation of BESSs in the LV grids directly influences any superimposed grid whenever the power peaks are shifted to times of lower grid usage during LV grid overload. To evaluate the effectiveness of the distributed storage regarding HV/MV transformer relief, the studied MV grid was used in a load-flow calculation. For the pictured backfeeding scenario, renewable generation with a simultaneity factor of 0.85 was considered; to reflect a worst-case scenario, no load was assumed. Storage was located at every LV bus within the indicated radius, r, around the HV/MV transformers, and the installed RET power exceeded the transformers' rated power. BESS power was chosen according to the overloading of the MV/LV transformers for the initial load flow calculation without storage. In Figure 37, the central storage refers to a scenario in which only one BESS was connected to each HV/MV transformer with half of the total power of all the distributed storage. For all of the different configurations, a load flow calculation for the backfeeding scenario was performed, and the HV/MV transformer loading and the grid losses were calculated.

While the distributed storage showed only slight differences in the absolute reduction of the transformer loading relative to a central storage grid, the losses decreased significantly with increasing storage distribution radius. Reduced grid losses were a result of the decreased power flow in the MV grid because the distributed storage stored a non-negligible share of the distributed generation. With a total storage power of 4 MW installed in the LV grids, HV/MV transformer loading can be reduced by up to 3.98 MVA.

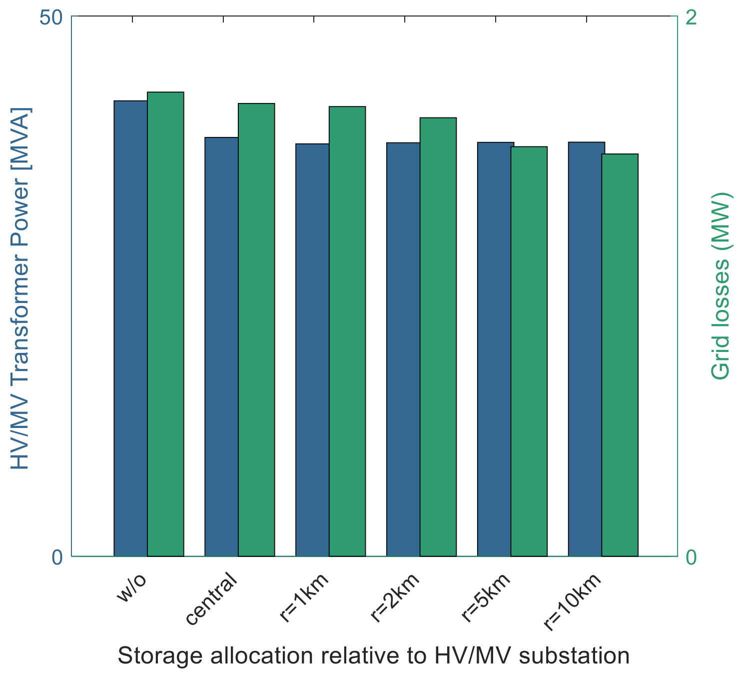

Figure 37 – Influence of LV storage on HV/MV transformer loading and MV mean grid losses (backfeeding scenario with high renewable feed-in and no assumed load) [39].

Thus, distributed BESSs can effectively reduce the loading of central resources with the added benefit of lower grid losses and reduction of local grid and transformer loads. While the extent of the HV/MV transformer unloading and the reduction in grid losses depend on the network configuration considered, the tendency remains true for all grids. A short comparison between the costs for the necessary transformer exchange costs with and without BESS installation in Table 18 shows the contribution BESSs can make. Further financial benefits can be achieved by operating the storage with increasing self-consumption and the provision of negative SCR.

Table 18 – Evaluation of cost savings regarding BESS installation in a varying radius around an HV/MV transformer station to combine the unloading of the MV transformer station due to installing BESSs in the LV grid [39] and according BESS costs for today and future prices (see Table 20, EUR to USD 12.12.2016).

Radius	Transformer exchange costs	Avoided transformer exchange costs	4 MW BESS costs today	4 MW BESS costs future
No BESS	1,490,000 €			
Central	490,000 €	1,000,000 €		
1 km	490,000 €	1,000,000 €		
2 km	454,000 €	1,036,000 €	2,310,000 €	1,382,000 €
5 km	394,000 €	1,096,000 €		
10 km	352,000 €	1,138,000 €		

In conclusion, LIB BESSs are suitable and, from a technical point of view, capable of installation in any grid level. However, the outlined analyses show that LIB BESSs operating in LV grids are provided by the technical configuration of these grid levels with additional room for APMs, which are not present in the MV, HV or XHV grids. Although the majority of BESS APMs are not economically viable under all circumstances, the addition of APMs onto a system seems to be an appropriate method for increasing the economic value of BESSs, which is one of the core issues of this work.

4.4 Case Study: Residential Home Storage

BESSs in the context of a single family home, i.e., residential BESSs, increase the connected households' SCR to minimize electricity cost, as shown in Subchapter 3.1. Currently, BESSs in this context store surplus energy generated from a local PV system, which is under legal unity with the house owner, and provide energy in times of low or no solar irradiation to compensate the load. In the future, a variety of use-cases for residential BESSs will occur; rising shares of electricity generation by local entities, such as private or shared PV systems or wind farms, will lead to further destabilization of the grid. However, the integration of residential BESSs in modern grids is currently mostly driven by benefits to individuals. Residential BESSs are built in houses that have PV systems installed and are mostly economically driven.

For end consumers, BESSs are most meaningful when they are economically beneficial and reduce a house owner's electricity bill; the net present value (NPV) of such an investment is at least positive for a given time period of operation. From a legal perspective, the integration of residential BESSs is uncomplicated. Many countries have enrolled in programs supporting the installation of residential BESSs because of the side effects that residential BESSs offer grid operators and regulators.

By simply changing the charging algorithm from strategy A, which is supposed to be greedy from the house owner's perspective, for example a strategy B can provide the identical benefit to homeowners and grid operators. Additionally, residential BESSs may have a positive influence on electricity grids. The motivation for DSOs arises from grid voltage stability, the maximum installable PV capacity and grid relief leading to reduced grid reinforcement demand.

On the Tesla Powerwall v1.0

The following material serves to give a brief overview of the results of the co-authored publication "Economics of residential PV-battery systems in Germany" [158] based on Tesla's Powerwall residential home storage system to better understand BESS operation in residential environments.

A proprietary power flow simulation model was implemented to assess the technical and economic outcome of a residential PV system running with BESSs [26]. A series of different configurations of household loads and PV systems was examined; the overall assessment took households from 1,000 kWh to 10,000 kWh into account with installed PV systems of 1 kWp to 10 kWp. The utilized load profile consisted of 15-minute values over an average of 100 households in Germany over the course of one year [180]; furthermore, the generation profile was measured with a sample time of one minute on a PV system in Munich, Germany in 2009 [158].

Table 19 – Reference scenario data based on Tesla and used for the case study simulation.

Name	Value	Unit
Usable energy capacity	6.4	kWh
Rated power	3.3	kW
Round trip efficiency (battery system only)	92.5	%
Battery chemistry	NMC	-
Time period until 80% capacity	15	years
Full cycles until 80% capacity	5,000	cycles
Price	3,615	EUR

In addition to the load and generation profiles, electricity price developments were set for two different scenarios: first, a constant electricity price of 28.72 ct/kWh [181] and, second, an increasing electricity price of 4.55% per year with a starting price of 28.72 ct/kWh in the first year of the simulation [182]. Simulation parameters according to Tesla's Powerwall were set for the same chemistry of LIB cells that Tesla uses, shown in Table 19. Simulations were carried out over a 20 year period, and BESS aging was set to an end of life (EOL) of 80% after 5,000 equivalent full cycles by using degradation curve fitting [164]. The BESS operation strategy was set to a greedy algorithm.

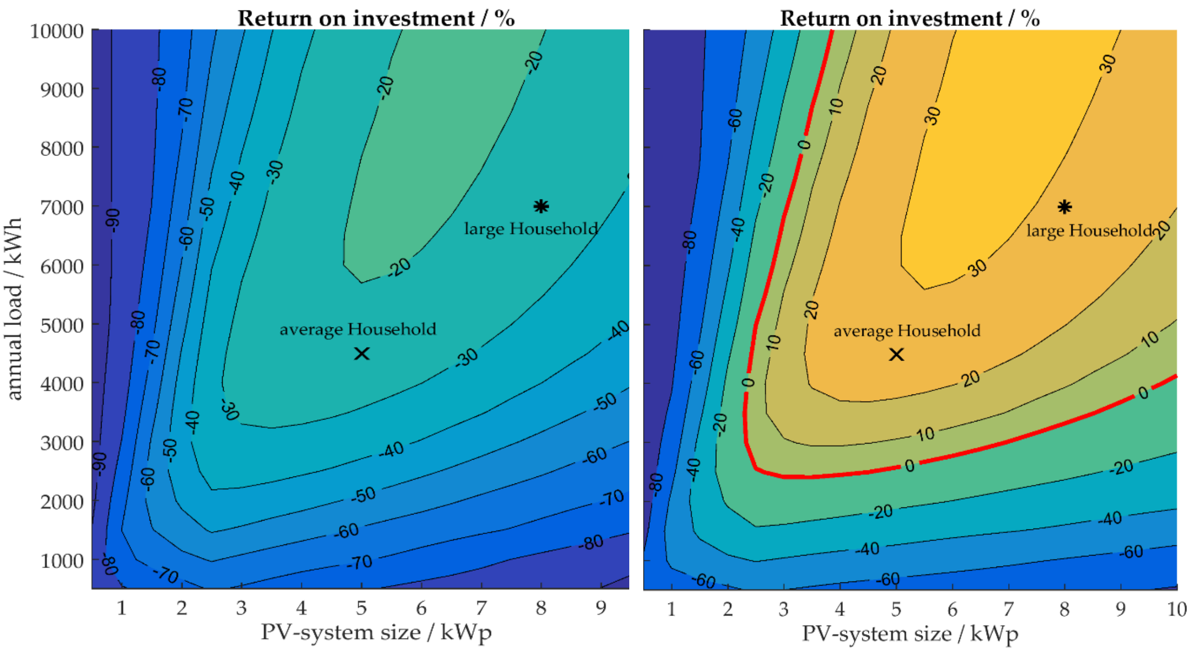

Figure 38 – ROI for the reference scenario over all the simulated PV system sizes and household loads. The thick red line emphasizes the savings threshold of the BESS with an ROI of 0%. (a) Results for the constant electricity price scenario and (b) results for the rising electricity price scenario [158].

The results, depicted in Figure 38, of the investigation clearly present the impact of a household's consumption and PV system size on the effectiveness of BESS. *The ROI increases with both the PV system size and the annual load until saturation is reached. As the figures* *depict, this effect results in a U-shaped contour. Neither the annual load nor the PV size directly correlate with the economics of the BESS. Instead, both variables yield matching values for the BESS to achieve the optimal ROI [158].*

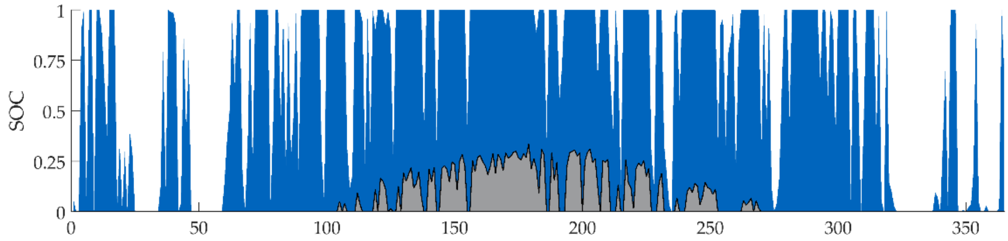

Figure 39 – The SOC-range of the BESS for each day is depicted in the blue areas whereas unused energy throughout a day is depicted in gray [158].

Figure 39 shows the utilization of the BESS, where the SOC-range is given for one year of operation. The blue area shows the SOC-range of each day, whereas the grey area illustrates the energy content of the BESS that is not consumed within the entire day. The resulting data was calculated with a 4,500 kWh household and a 5 kWp solar system over one year. The results indicate, that a) the average load of a household in Germany is not sufficient to use all stored energy in the BESS, i.e. due to high solar irradiation during summer days and thus high self-consumption of the PV power itself, and b) that, due to weather effects, a household's BESS has a low capacity factor over the course of one year if only used with a single APM. Residential BESS systems, mostly independent of the operation strategy, are highly dependent on the overall configuration of the system. This coupling will dissolve in the future if rising electricity prices, falling feed-in tariffs, and or falling BESS prices can be assumed. A residential BESS, additionally, will gain more attention when coupled with electromobility, which can used in BESS swarms or shared economy, coupled with smart home technology, steering charging regimes of vehicles, that require temporarily large amounts of energy and especially power.

On feed-in tariffs

The feed-in tariff was the most preferable option for selling electricity generated by PV power plants until grid parity was attained in the year 2012.

Grid parity describes the decline in the feed-in tariff below the current electricity price for household customers. In 2014, this guaranteed subsidy contributed significantly to the coverage of approximately 6.9% of the net electricity consumption by PV energy. The legal remuneration entitlement of the plant operator against the grid operator for each supplied kilowatt hour of electricity is still a predictable and safe source of income for an investment in a PV plant. The annual high numbers of new installations in Germany, which were favored by the fixed feed-in tariffs, have contributed to the significant cost reductions in PV modules. With the amendment to the EEG 2014, the legislature has decided to reduce the feed-in tariffs and to prioritize direct selling. In the future, the feed-in tariffs will be gradually reduced with the addition of installed capacity, which should allow PV technology to participate in the free market.

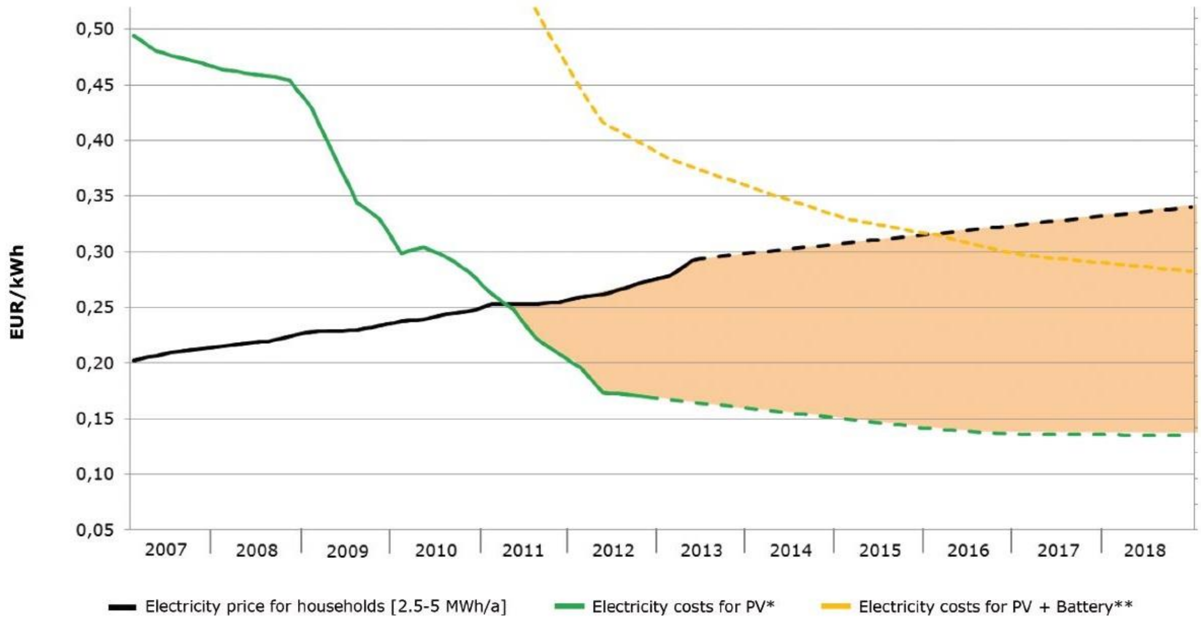

Figure 40 – The German PV Market reached Grid-Parity in 2011. The expanding gap between PV-LCOE and electricity prices improves the economics of batteries. */ Model calculation for rooftop systems, based on 802 kWh/kWp (Frankfurt/Main), 100% financing, 6% interest rate, 20 year term, 2% p.a. operation and maintenance [183].**

The fixed feed-in tariff represents the greatest obstacle to the development of business models for selling the generated electricity locally. The business models must offer the plant operator an economic advantage in comparison to the riskless and uncomplicated feed-in tariff. In particular, the economical amortization of a battery storage system depends on the level of remuneration of the alternative grid feed. The taxation of the feed-in tariffs depends on the respective corporate law usage of the PV plants. Figure 40 depicts grid parity for PV system without (green line) and with a storage system (yellow line) for Germany under the given economic assumptions.

On self-sufficiency

Self-sufficiency as defined in § 5 number 12 EEG 2014 includes electricity "which a natural or legal person consumes himself in the immediate vicinity of the electricity-generating installation if the electricity is not fed through a grid system and this person operates the electricity-generating installation himself." As a result of the reduction in the fixed feed-in tariff under the current electricity price, self-sufficiency with the generated electricity has become a basic condition for the profitability of a PV plant. PV plant operators can consume a certain proportion of their produced electricity, and they still receive the fixed feed-in tariff for electricity fed into the public grid. Battery storage systems can significantly increase the share of the self-sufficiency under certain circumstances. The economic impact of this increase is explained in the technical analysis and the profitability calculation.

4.5 Case Study: Apartment Buildings and Multi-Family Houses

In spite of a variety of imaginable constellations for BESS implementation, there are certain scenarios lacking attention in the scientific community, especially since BESSs for single family houses are currently close to profitability (as of 11/2016) [171, 184–186]. In Germany, 41.21

million people live in 18.62 million apartment buildings comprised of 35.78 million apartments, Figure 41 depicts a multi-family house with four tenants, which represent a new group for potential BESS installation, and 15.47 million single family homes host 28.98 million Germans. The PV and BESS potential in urban regions where most apartment buildings are situated should be analyzed. There are several reasons to install BESSs in urban areas, including the upcoming transition to electromobility, digitalization and smart home technology, and unused roof space and flat roofs in city and urban areas for PV installation. The following discussion will address how LIB BESSs can be operated in apartments in Germany and show simulation results for these BESS.

First, in apartment buildings, i.e., multi-family houses, BESSs target paths identical to suburban BESSs, which serve homeowners by maximizing their SCR of RETs and decreasing the electricity cost. Relative to a single family home, the load profile of multi-family objects is much more diverse, and a more complex owner structure prevents fast assumptions of BESS performance in such environments. Other regulatory requirements or legal restrictions, which must be applied for multi-family BESSs, hinder the business models for such systems. Additionally, the available roof area for shared PV systems limits BESS sizing and power. Implementation of multi-family BESSs is still highly probable because of the necessity of a widespread energy shift toward greener energy and future consumer behavior regarding electromobility and smart homes.

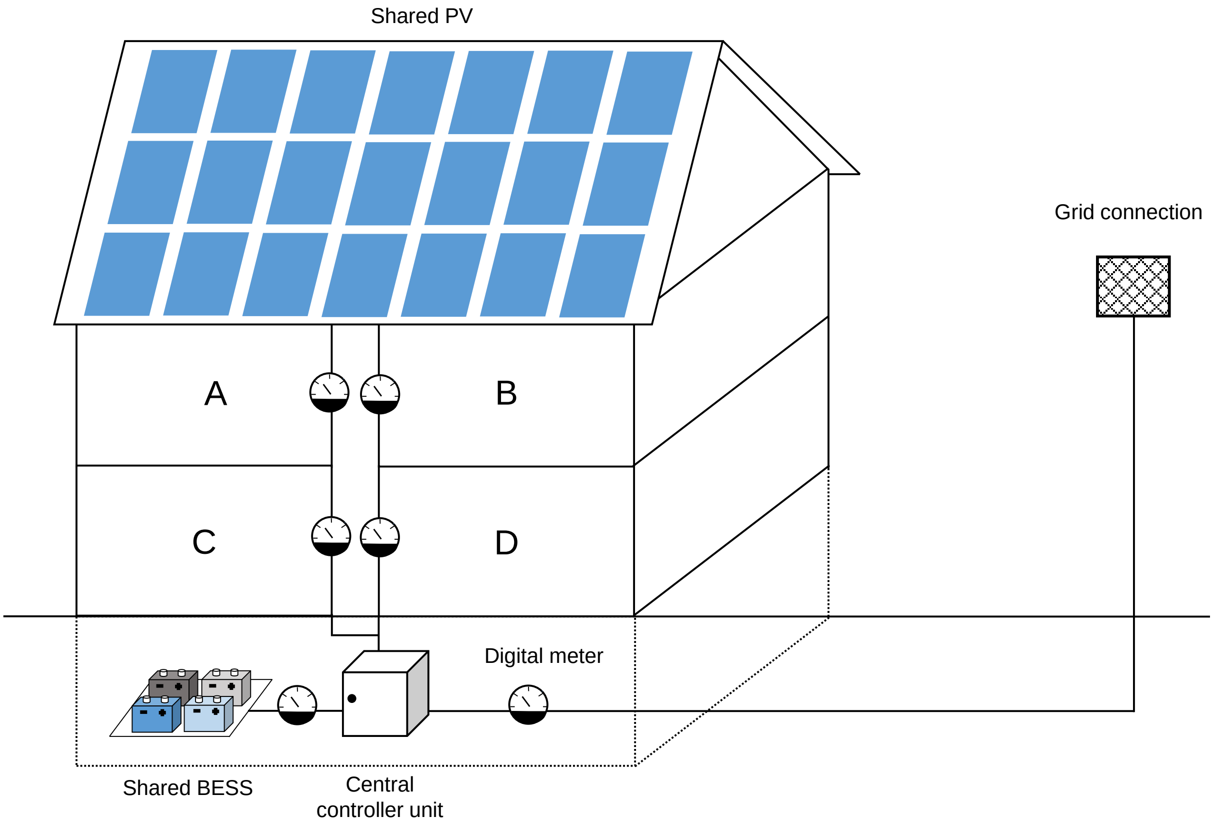

Figure 41 – A multi-family house with four tenants, a shared BESS and the according metering setup

Figure 41 depicts one possibility of a multi-family house comprised of a shared BESS, a shared PV system and the according metering concept. The overall benefit, regardless of investment costs and subsidies (which range significantly between countries and markets), of a BESS in an apartment building can be described similarly to the case for single family houses as the building's total electricity costs, $C_{electricity_{total}}$. $C_{electricity_{total}}$ is the yearly consumed energy, $E_{consume}$, multiplied by the building's electricity price, C_{kWh}, per kilowatt-hour.

$$C_{electricity_{total}} = E_{consume} * C_{kWh} \tag{19}$$

Thus, for an apartment building with more than one apartment, apt,

$$\begin{aligned} C_{electricity_{total}} = &\left(\left(\sum_{1}^{n=apt_{max}} E_{consume_{apt}}\right) - E_{solar} - E_{BESS_{solar}}\right) * C_{kWh} \\ &- \left(E_{feedin_{solar}} - E_{curtail} + E_{BESS_{curtail}}\right) * C_{feedin} \end{aligned} \tag{20}$$

Within the multi-family house, all the apartments have their own electricity consumption meters to measure the amount of energy they consume. Initially, the PV power plant feeds the generated electricity into the house network of the multi-family house and satisfies either the electricity demand of the tenants or recharges the battery storage system. The surplus electricity is subordinately fed to the public power grid. A two-direction meter at the house connection point measures the feed-in and the purchase of electricity during a lack of PV power production and a discharged BESS. This two-direction or digital meter can measure both the purchase from the public grid and the excess feed-in, and it is required in the measurement concept for communication with the DSO as well as for the correct accounting of the energy quantities in the building with the utility. Any electricity delivery within a multi-family house represents a supply of electricity within a house network that is not expressly carried out via the public power grid. The supply without usage of the public power grid has an impact on the legal and fiscal treatment of the electricity delivery. Therefore, this supply constitutes an essential component for the explanation and assessment of the business models. An additional delivery of the main electricity by an energy supplier to meet the demand during heavy load periods or missing PV power production in the multi-family house is excluded from exemptions of individual electricity price components. These concepts for selling electricity in multi-family houses can be transferred to significantly larger properties. The key criteria for consideration is the difference in the persons between the plant operators and final consumers. In the past, the building owner or a strategic investor traditionally undertook an investment in a PV power plant on a multi-family house. Because of the high guaranteed feed-in tariffs, PV systems were conceptualized and geared toward maximum profit. An analysis of the actual load profile of the multi-family house was not conducted. With the reduction of the rate of subsidy and lower PV module prices, a differentiated picture now results. To operate a PV power plant economically, the current feed-in tariffs are no longer sufficient. Business models described here aim to achieve the highest possible rate of direct consumption for the produced PV electricity. The direct consumption rate of a PV system is introduced as follows. The direct consumption rate does not differ, technically, from the SSR of a single-family house.

$$DCR = SCR = \frac{E_{sc}}{E_{PV}} \tag{21}$$

The difference between the SCR and the direct consumption rate (DCR) is in the legal definition of self-sufficiency and direct consumption and results in a different burden of taxes, duties and levies. The introduction of this new concept is necessary to ensure a clear distinction between taxes, duties and levies in the further course of the thesis. In these business models, battery storage systems are primarily used to increase the amount of energy that is directly consumed. In most cases, this approach leads to a substantial increase in the DCR. The share of self-consumed electricity from the PV system in the total energy consumption is defined by the degree of self-sufficiency and determines the composition of the electricity price for the end consumer and the profitability of the price quotation. This description serves as a general description of the scoped benefits and fundamental understanding of BESS operation in a multi-family house or apartment building. In an apartment building, a broader variety for handling PV surplus energy exists in addition to the aforementioned cost calculations. The following discussion provides a brief outline of the legal framework and general possibilities for operating an LIB BESS in an apartment building. According to the EEG 2014 [187], an operator of a PV plant has the choice of three options for selling his generated electricity. The intermediate storage of PV electricity has no legal effect on the selling possibilities since the type of production plant is decisive for the selling option. Apart from that, the PV plant operator also has the option of not feeding the electricity into the grid of the public energy suppliers and consuming the electricity. This so-called self-sufficiency is defined in the law as the consumption of the electricity "in the immediate vicinity of the electricity-generating installation" by the plant operator. In addition to the self-sufficiency, the plant operator can choose from the supported direct selling as per § 20 EEG para. 1 sentence 1, other direct selling as per § 20 EEG para. 1 sentence 2, or a feed-in tariff as per § 20 EEG para. 1 sentence 3.

To draw further conclusions from the given setup several simulations were carried out. For simulation purposes, contrary to single-family homes, load profiles of multi-family houses are not available as standardized profiles. To achieve a realistic simulation environment, a set of 74 [188] single-family home load profiles are combined randomly for the generation of a multi-family house load profile. The resulting profiles were compared towards H0 standard load profiles and their similarity calculated.

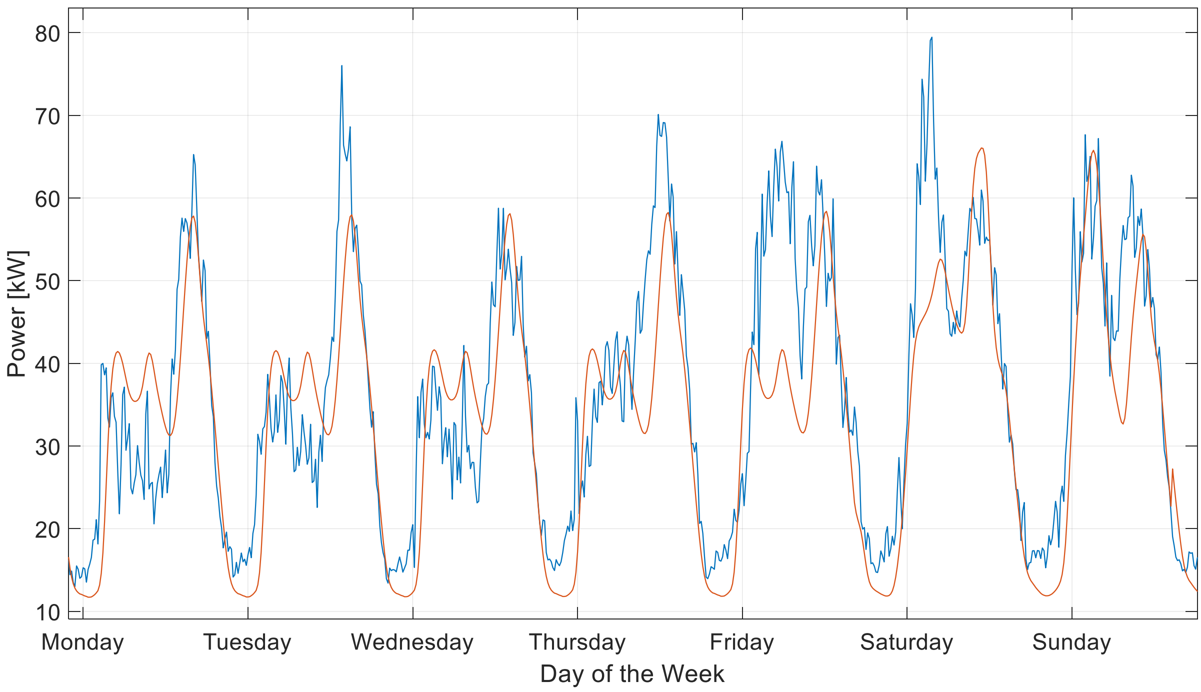

Figure 42 – Comparison of standard load profiles H0 (orange) for 1.000.000 kWh per year and calculated multi-family house load-profiles (blue) from field data for a winter week in 2016.

Figure 42 shows a standard load profile H0 (orange) and the synthesized load profiles for a multi-family house (blue). While general differences can be observed, the resulting data shows a sufficient quality for further simulations, with higher resolution than the H0 profiles.

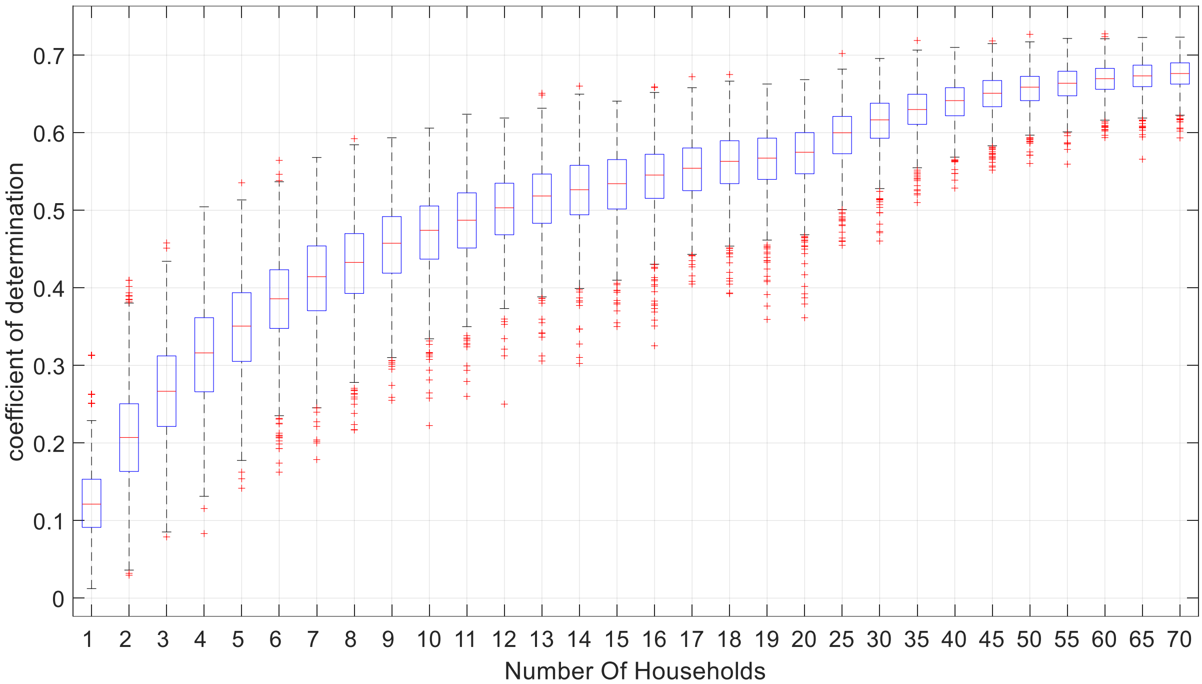

Figure 43 – Resulting degrees of certainty for a number of household profiles, combined to a single multi-family house profile set and resulting similarity coefficient, compared to a standardized load profile H0.

Figure 43 shows the resulting coefficients of determination for an increasing number of households which profiles were added onto each other to generate a multi-family environment. Each boxplot thereby represents a set of 100 different combinations of the given 74 single household profiles which were randomly chosen for the generation of a multi-family profile. The data indicates, that the generation of a multi-family house load profile achieves a mean coefficient of determination of about 0.33 for a combination of four single-family household profiles over one hundred simulation runs. Hence, to increase reliability of results for final simulations, a load profile consisting of 30 households, averaging at a coefficient of determination of about 0.55, was used.

The simulations were carried out similar to a single-family BESS with the simple greedy algorithm; see Subchapter 3.5. Figure 44 shows the resulting DCR for a varying number of household ranging between 1 and 70; the PV-systems peak power ranges from 5 to 200 kWp; and the storage size between 0 and 200 kWh of capacity. The results indicate that the technical and economic evaluation of a multi-family house shows similar results to these of single-family houses. Given the similarities and load profiles for the calculation, see Figure 42, these results confirm aforementioned analyses. In general, it can be observed that a fixed number of households will show higher DCR for smaller PV systems and larger BESS sizes. Accordingly, a fixed PV-size shows higher DCR for more households and larger BESS sizes. Accordingly, a fixed BESS size shows higher DCR for more households and smaller PV systems. Generally speaking a multi-family house shows no significant differences compared to a single-family house for PV coupled BESS operation to increase SCR/DCR. The main hurdles to overcome yet are to be seen in the regulatory framework.

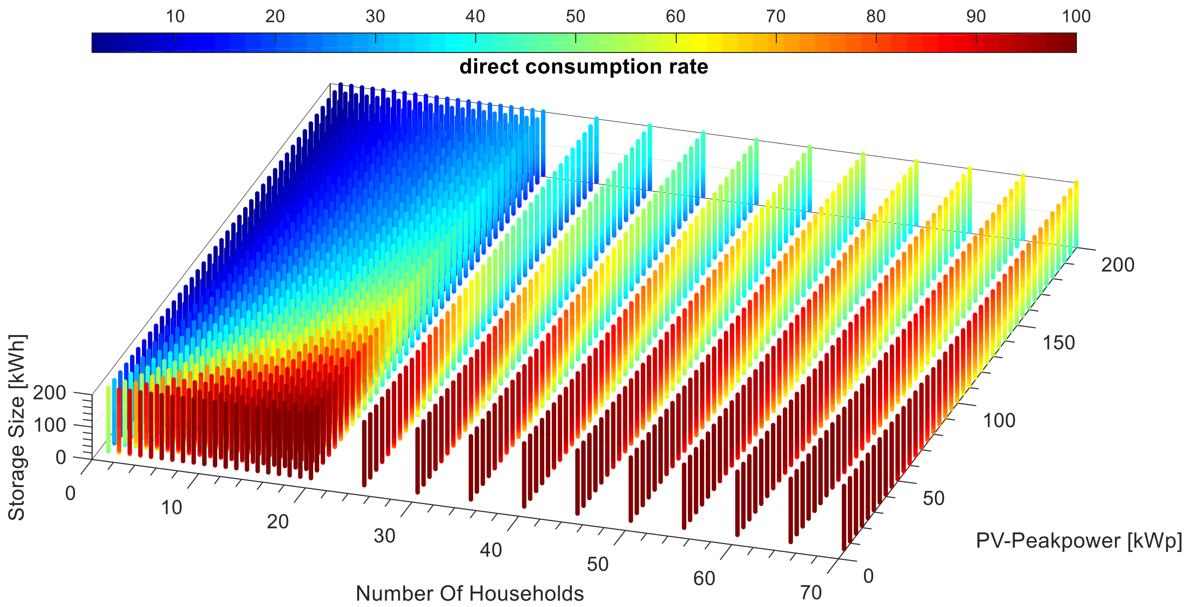

Figure 44 – DCR for a range of households in a multi-family house coupled with a shared PV-system and a shared BESS. Number of household range between 1 and 70; the PV-systems peak power ranges from 5 to 200 kWp; and the storage size between 0 and 200 kWh of capacity.

On supported direct selling and other direct selling

With the renewal of the EEG, the legislature tightened the responsibilities of the operators of electricity generation plants and made direct selling the standard selling option in the EEG. According to the legislator, the direct selling of electricity from renewable energies and electricity from PV plants comprises the sale to third parties when the electricity is passed through a grid of public utilities and is not consumed by third parties in direct proximity to the installation § 5 number 9 EEG 2014. Both the supported and other direct selling is the sale of electricity to a bulk purchaser or directly at the European Energy Exchange (EEX) in Leipzig. To promote the direct selling of electricity from renewable energies, the legislator guarantees a remuneration at least at the level of the feed-in tariff due to the market premium model. The market premium compensates for the difference between the electricity price at the EEX and the fixed feed-in tariff. In addition, the plant operator can generate further profit by selling the electricity at peak load times at the EEX. Figure 2 shows the difference between the fixed feed-in tariff and direct selling according to the market premium model. The EEG 2014 introduced a gradual obligation to direct selling. For new installations with a total power of more than 500 kW from January 1, 2016 and for installations over 100 kW, direct selling is required. In addition to the supported direct selling in the market premium model, the other direct selling option is still an available alternative. The other direct selling option is the direct sale of electricity at the EEX without any subsidies or promotion of the EEG. This selling option is still not profitable and therefore not prevalent for PV plants.

4.6 Case Study: Primary Control Reserve

The following material will show in detail the ways in which BESSs can participate and deliver PCP. The results presented here have also been summarized in the , "*Fundamentals of using BESS for providing Primary Control Reserve*" [137].

Regarding BESS's capability of providing PCP during a long timeframe, the available energy content must be sufficient to deliver the demanded power. Therefore, the ENTSO-E released (similar to demand up or down codes in the U.S. by selected states) regulations for BESS. These regulations state that BESSs acting as a power system provider have to hold at least enough energy to provide the full tendered power for over 30 minutes $t_{PCP_{30}}$ without recharging from the grid or other sources. The same regulation previously required 15 minutes $t_{PCP_{15}}$. Based on these regulations, formulas (1) and (2) deliver the minimum and maximum SOCs for a prequalified power, P_{pq}.

$$SoC_{max} = \frac{E_{batt} - \mathrm{t}_{PCP} \cdot P_{pq}}{E_{batt}} \tag{22}$$

$$SoC_{min} = \frac{\mathrm{t}_{PCP} \cdot P_{pq}}{E_{batt}} \tag{23}$$

Figure 45 depicts the ratio between capacity and prequalified power for the SOC of BESSs when operating in PCP APM.

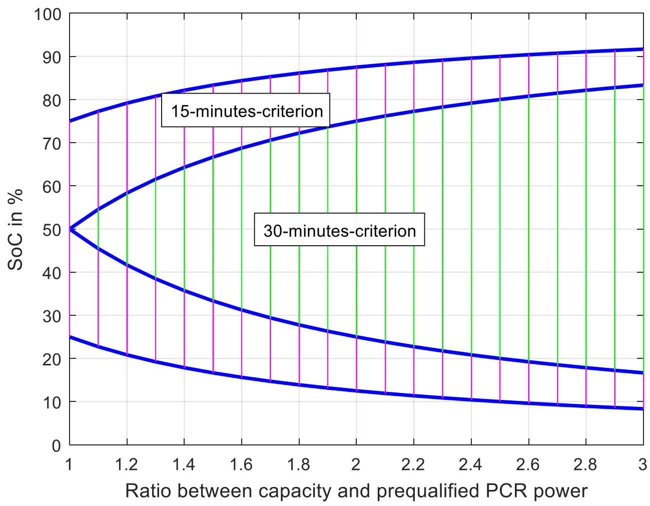

Figure 45 – Required SOC range for a BESS as determined by the 30 or 15-minute criterion for a worst-case PCP requirement; a C-Rate of 1 C.

The 15-minute criterion allows larger SOC ranges for BESSs at low capacity-to-power ratios, e.g., a ratio of 1:1, which reflects a C-Rate of 1 C, within the 15 minute criterion corresponds to an allowed SOC range between 75 and 25%, and within the 30 minute criterion the SOC must be strictly 50%, which prohibits BESS operation within this ratio under the 30 minute criterion. Thus, BESSs have to operate within the given boundaries when providing PCP to comply with the regulators' guidelines. There are, however, exceptions to this necessity in case the grid frequency shows abnormal progressions [189]. Exceptions from the normal operation of BESSs in the allowed SOC ranges apply whenever there is a frequency deviation of δ_f as follows:

- δ_f > ±50 mHz for more than 15 minutes applies
- δ_f > ±100 mHz for more than 5 minutes applies
- δ_f > ±200 mHz applies

If any one of the above criterions is fulfilled, the operators of BESSs providing PCP are given a two-hour time frame to restore a permitted SOC according to Figure 45. This is specifically for the analysis of historic frequencies necessary to achieve maximum utilization of BESSs providing PCP.

> *In order to keep the battery SoC within the permitted range, several degrees of freedom (DoFs), as defined in, are granted by the German TSOs. The DoFs presume that the operators of PCP plants deviate slightly from the supply characteristic given in Figure 21; they are described in more detail below. The control power demand as indicated by the P-f characteristic can be increased up to 20% at any time in order to modify the SoC. The control power demand as indicated by the P-f characteristic can also be provided within the tolerated deviation range of ±10 mHz if the SoC needs to be adjusted. The control power demand as indicated by the P-f characteristic must be provided within 30 seconds or less. As appropriate for the current SoC, this minimum gradient can be used in order to slow down the charging or discharging process of the battery. The most important way to reach the desired state of charge is by trading energy on the electricity market. By selling or buying energy on the European Energy Exchange (EPEX), the SoC can be decreased or increased as required. This can be performed simultaneously with providing the PCP power. [190]*

As an application of the mentioned degrees of freedom, following the power-frequency characteristic, BESSs are fully able to provide PCP under the mentioned conditions.

4.7 Case Study: Island Operation

Subchapter 4.7 gives a brief overview of a case study, “Sustainable power supply options for large islands – a case study for Belitung Island” [191] co-authored by the author, that examines the island of Belitung, Indonesia to gain a better understanding of BESS operation in island grids. The operation of a BESS on an island can be evaluated from two different perspectives. First, from an environmental perspective, i.e., decreasing carbon emissions on islands by reducing fossil fuel demand, and second, from a technological perspective, i.e., developing future reliable grids with the assistance of storage technology. The power demand of islands, specifically in highly populated areas such as Southeast Asia, is expected to increase rapidly over the next several decades. In many areas where such an increase is projected, e.g., the island of Belitung, Indonesia, large fossil power plants are planned to accommodate the upcoming demand. It is therefore appropriate analyze the impact of BESSs on the reduction of carbon emissions in such an environment, and a simulation model was developed to identify possible cost-effective integrations of BESSs on large islands. A mixed binary integer linear programming model fits power generation technologies and storage technologies with hourly resolution to serve the electricity demand at demand points. Electricity may be transported from one demand point to another via transmission lines. At each demand point, any demand must be covered hourly by either generation, storage or import from surrounding demand points.

Distribution losses are addressed using a loss factor for transmission lines. In addition, the distinction between controllable and non-controllable generation technologies is outlined. Thus, the hourly output of coal, diesel, biomass, and geothermal power units has to be within zero and the respective generation capacity. In contrast, PV or wind are input values from solar irradiation or wind power profiles over a simulation year. Demand points are defined according to the island's administrative areas, depicted in Figure 46, which refer to village-sized communities. The annual power demand in each demand point is matched with its population and average household size. Power demand development scenarios are taken from the Indonesian governments reports [192] with an annual increase of 13% [193].

The demand point setup for residential areas, i.e., monthly electricity consumption data on Belitung, was derived from survey data [194], which totaled up to 1,284 GWh annual energy consumption in 2030. Data for the technology setup were taken from [195] and [196] and include data for diesel generator units, coal power plants, solar PV, biomass, geothermal and wind. Data for BESSs were based on the knowledge and data from this thesis. To fit the model, four BESS (only LIB systems) categories were considered: category 1: home/residential BESSs; category 2 and 3: community and multifamily house BESSs; category 4: large-scale BESSs in the MV grid. The main assessment was based on a non-carbon reducing simulation of the model.

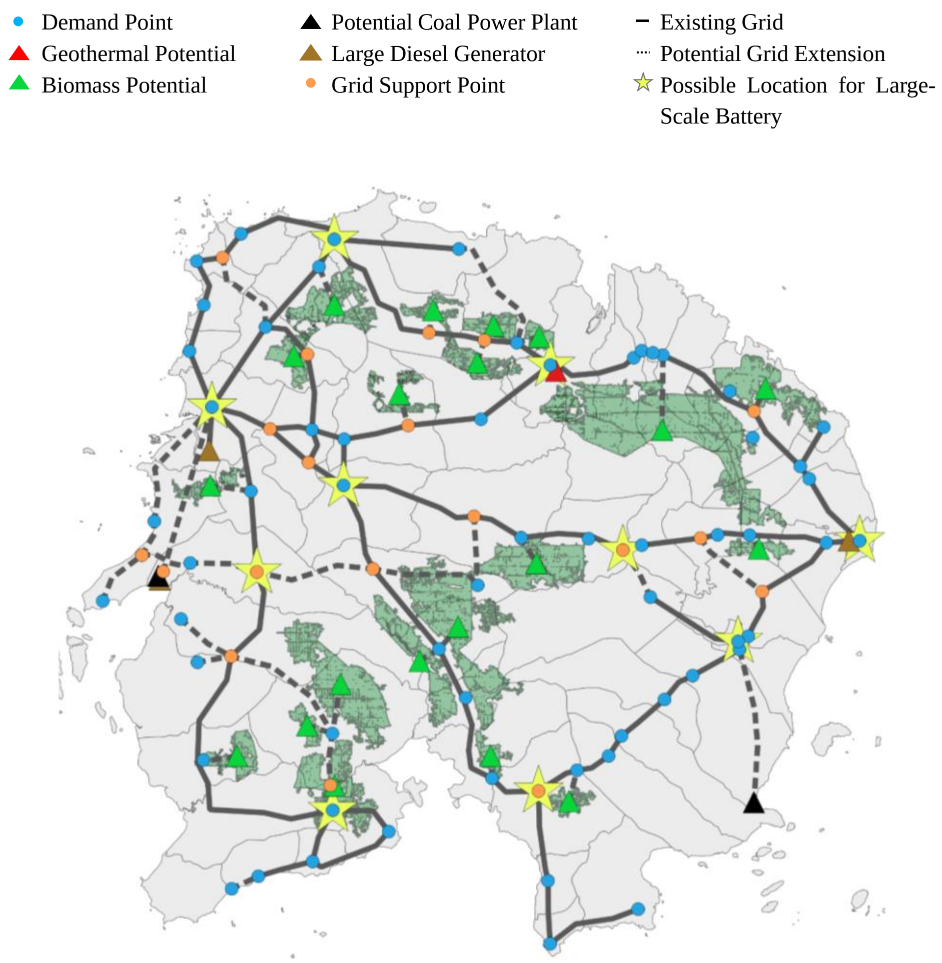

Figure 46 – Belitung Island with all considered model demand points, generation points and transmission lines [191].

No carbon emission restrictions for Belitung Island were set; this scenario was used as a carbon reduction reference. The prices for generation, transmission and demand were set for 2016 and a future pricing scenario, BESS pricing, was set according to Table 20. The costs were determined by a comprehensive study of available BESS in the market worldwide as of 03/2016. Therefore, market price data of n = 293 commercially available BESS were listed of which the 15th quantile data, representing the most cost-effective market leaders, were used for this research. In order to extrapolate the future cost of stationary BESS, a yearly decline of 8% for battery cell cost, a 5% decline for power electronics and a 2% decline for auxiliaries, based on [44] were utilized. Table 20 shows the extrapolated cost structure for different types of BESS in 2026 based on the aforementioned estimations.

Table 20 – Investment cost analysis for today and in the future for BESS categories 1 to 4 (n = 293). [191]

No.	Investment Costs 2016 [USD/kWh]	Total Price Reduction [%] from 2016	Investment Costs 2026 [USD/kWh]	Round-Trip Efficiency	Minimum Capacity [kWh]	n
1	1073	54%	579	0.9	-	212
2	998	52%	553	0.9	15	59
3	912	48%	517	0.9	350	16
4	612	34%	366	0.95	1000	6

The aim of the simulations was to establish, under all the constraints, a version of Belitung with the highest economic value, i.e., the cheapest possibility for energy coverage. The model therefore can built generation units, reinforce transmission lines, and develop storage units.

Figure 47 shows the simulation results for current and future storage costs of BESSs as well as carbon reduction scenarios for 0%, 25%, 50% and 75% from the reference scenario. Without any carbon emission restrictions, the electricity demand is mainly supplied by fossil fuels, i.e., coal-fired plants. Remarkably, this outcome reflects Indonesia’s current policy to accommodate future electricity demand on Belitung.

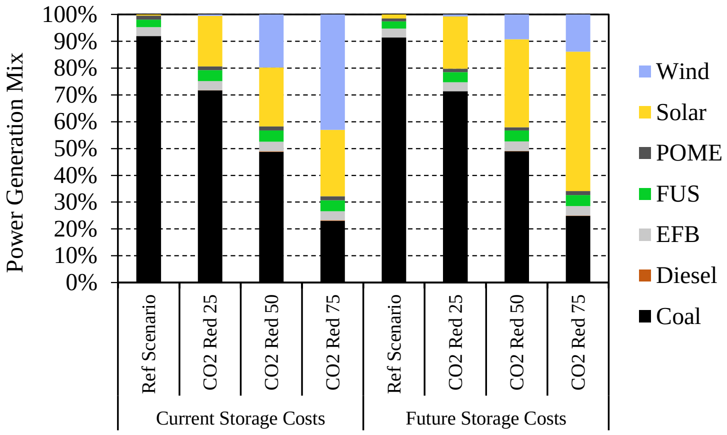

Figure 47 – Resulting power generation mix for the analyzed scenarios for Belitung Island. ***Abbreviations: empty fruit bunches (EFB); fiber and shell (FUS); palm oil mill effluent (POME).***

Furthermore, any biomass potential is already used in the non-reduction scenario; therefore, it is used throughout all the simulation scenarios. A reduction in carbon emissions leads to a significant decrease in fossil fuel energy generation, which is mainly covered by low LCOE PV energy, and wind energy is only used in higher carbon emission reduction scenarios because of its higher LCOE and CAPEX costs. To accommodate the electricity demand in higher reduction scenarios, e.g., 50% or 75%, fluctuating energy must be stored in BESSs and shifted from daytime to nighttime, i.e., from high solar irradiation times to low solar irradiation times and from high wind power times to low wind power times. Figure 48 depicts the usage of BESSs to shift the power accordingly, but only with future BESS costs are significant amounts built. This reflects the overall PV installation, depicted in Figure 47, which stagnates in scenarios of 25%, 50% and 75% at current storage costs. Lower future storage costs lead to a higher adoption of BESS in general, which will lead to a higher share of PV because of a) lower CAPEX costs in exchange for higher LCOE wind energy and b) the general suitability of storing PV energy due to day/night cycles.

For all of the simulations, the CO_2 abatement costs were calculated, as shown in Figure 48, by dividing all of the additional total annual costs compared to the respective reference scenarios by the reduced CO_2 emissions. The results show that the abatement cost is directly linked to BESS pricing because of the relatively high LCOE for wind electricity generation and the preferred installation of PV + BESS combinations. However, the CO_2 abatement costs are in general lower than comparable studies suggest; Malaysia and Singapore's estimated CO_2 abatement costs range between 45.2 and 84.4 USD per ton of CO_2 [197].

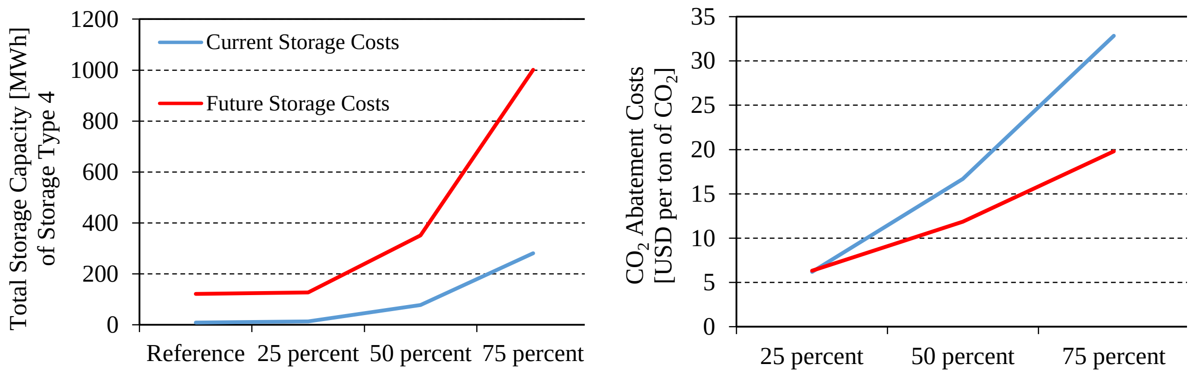

Figure 48 – BESS capacity (left) and CO_2 abatement costs (right) in all carbon emission reduction scenarios. [191]

The case of Belitung Island shows that BESS installation in island grids represents an alternative to other technologies. Areas of relatively high solar irradiation, such as the Southeast Asian region, benefit from PV + BESS combinations, as much more energy can be stored during the day. In addition, the typical load profile in the described areas differs widely from the European profiles. Where European load profiles show typically a morning and afternoon/evening peak due to vast electrification and personal electronics, ASEAN load profiles are rather flat during both day and night due to a) the lack of personal electronics in households and b) AC units which typically run without interruption or load peaks. Thus, BESSs can be implemented with different sizing under optimized operational strategies for lower LCOE of PV and better provisioning of solar energy throughout the year. However, only a low price scenario for BESSs allows this technology to be implemented in governmental policies in the aforementioned geopolitical areas.

4.8 Conclusion

Within the scope of this chapter, two excursuses and five case studies were analyzed and provided information to yield a broad understanding of LIB BESSs in different markets and varying APMs. Chapter 4.1 provides an overview of the economic value of APMs for BESSs when such systems are implemented in different grid levels (LV/MV/HV). BESS technology, first and foremost the LIB technology, is highly adaptable for any grid level; however, the overall potential for the greatest positive influence on the grid and a systems' economic value is better in certain grid levels than others. Because of a nearly unbounded ratio choice between power and energy, BESSs are suitable for a flexible design to serve any APM in any grid level. (See Subchapter 2.1 for more information on BESS design and system architecture.) A comparison between BESSs installed in different grid levels reveals that many of these systems can operate, in theory, within positive economic values. However, until now, there has not been a wide range analysis of MP-BESS to increase the economic value or positive effects on grids by systematically stacking APMs and increasing the utilization of BESS, which would result in a lower CAPEX.

In general, the integration of BESSs in LV grids allows the operators of such systems to provide nearly any APM that has been identified, see Subchapter 2.3. A BESS in an LV grid can provide frequency regulation services for grid stability, increase the SCR for a community, thus saving electricity expenses, and provide local UPS functionality, among other favorable results. The results show that LV grids are of interest because LV BESSs can serve any APM that an MV or HV BESS serves, whereas an MV BESS cannot serve certain LV APMs. Substituting a large central MV BESS, e.g., a 5 MWh and 5 MW central BESS, with smaller entities, e.g., 10x 500 kWh and 500 kW decentral BESSs in an LV grid level, allows operators of these to offer APMs in the LV grid in addition to the MV grid level and extend to MV and HV grid APMs. Drawbacks are higher installation, maintenance costs and higher coordination effort between a fleet of decentral BESS.

The results from analyzing BESS behavior when operating as residential home storage assume that BESSs for single family homes will become economically viable over a broader range without subsidies in the near future. However, this expectation seems to depend largely on electricity prices and regulations; thus, it should not be used for economic market predictions in the future.

BESSs operating in multi-family homes were analyzed and examined from a legal point of view. BESSs in a multi-family home environment can only be operated in a meaningful way by establishing a consistent smart-metering concept. Thereby, such concepts need to ensure that any legal circumstances given by laws and regulations, e.g., tenant freedom to choose their electricity provider, remain valid. However, apart from legal concerns for such concepts, BESSs in multi-family environments lack economic value mostly because of the low ratio of PV system size and load. In general, either subsidies or decreasing prices for BESSs will lead to the broader adaptation of BESSs in such environments.

Regarding operating a BESS for ancillary services, i.e., PCP in the outlined case study, the 30 minute and 15-minute requirements for prequalification have been investigated in detail. Generally, if the boundaries that have been set by the German TSOs for PCP hold true, BESSs can provide PCP with high quality. BESS operation with APM PCP yields positive income and, for Germany, several large systems have been and will be built. However, market limitations in size and flexibility may lead to a decrease in revenue and ultimately to a recession in this market when BESSs have fully supplanted other technologies in the future.

The appearance of increasing CO_2 reduction in potential energy production on islands leads to higher costs for systems powered with BESS assistance. This effect, as of the current prices, is fundamentally based on the pricing of such systems. However, it is unclear whether BESSs yield the most economic and technically feasible results for reducing CO_2 emissions in scattered island areas worldwide because of the economic differences between continents, regions and countries. It can be seen, however, that a RES – BESS combination will yield positive revenue streams after a few years of operation. Especially high fossil fuel costs could lead to investments into RES – BESS instead of diesel generators; the main challenge remains the large investments which is needed upfront for the implementation of a large RES fleet coupled with BESS.

5 Multipurpose BESSs: Technical Aspects and Simulation Model

In the beginning of this thesis, the basic concept for MP-BESSs based on LIB technology was introduced. The potential of the MP-BESS concept is expected to show strong increases in the current economic value of LIB BESSs since the implementation of such a system is technically possible but lacks a suitable legal framework in Germany, Europe and most parts of the industrialized world. Additionally, the multiple use of a BESS was explained, as was the influence of stacking multiple APM on a single BESS on BESS characteristics, i.e., aging phenomena. A general description and experimental description of MP-BESSs are given in the following chapter.

In Subchapter 5.1, in addition to the logical and technical concept, the operation and simulation of an MP-BESS will be shown in more detail. Subchapter 5.2 explains in detail the possibilities of BESSs seen as MPT. Based on these factors, an operational model and the optimization potential and economics of experiments with an MP-BESS are presented and tested by showing the influence of APM stacking on BESS aging in Subchapter 5.4. In Subchapter 5.2, the simulation method and model for an MP-BESS are given; in addition, the potential for optimization of BESS internal technical parameters to further enhance the performance of such systems is evaluated in Subchapter 5.5. Subchapter 5.6 will outline conclusions on the economic value of such a system under the auspices of German law and regulations. Finally, Subchapter 5.7 will conclude the matter and provide prospects for future evolution of BESSs as MPT.

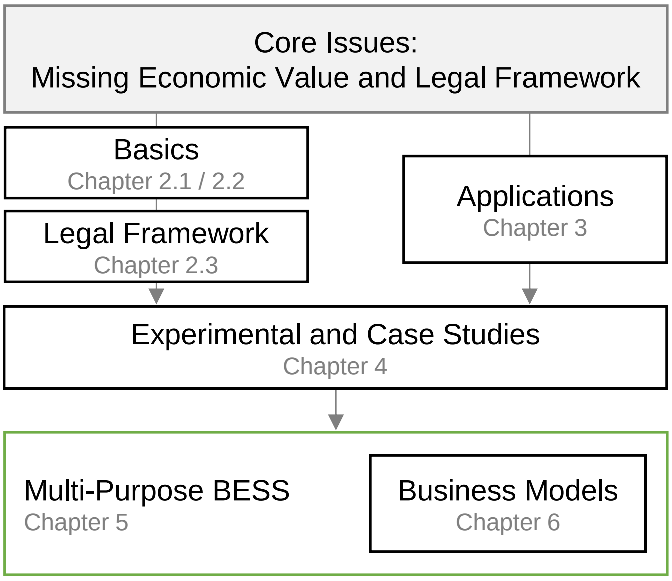

Figure 49 – Work progress in Chapter 5.

5.1 Basic Concepts for the MPT BESS

The following discussion will describe a possible technical solution for MP-BESSs, defining the BESS as an MPT carrier. First mentioned by [198] (see Subchapter 1.2), BESSs as an MPT carrier were explained concisely by reviewing the technical setup of such systems, briefly comparing them to other multi-use technologies and reviewing the benefits of BESSs as an MPT.

Transferring the idea, referring to Subchapter 1.2, of an MPT to SES/BESS offers multiple ways to generate additional revenue streams by combining several applications into one functional system. MPT has been defined as "*a […] technology […] that has several distinct, economically relevant applications primarily focused on one or a few sectors, yet lacks the technological complementarities of general-purpose technologies*." [198] The following will briefly introduce the three different approaches for MPT-BESSs and define each approach depicted in Figure 50, which has illustrations of the following explanations and differentiates three exemplary MPT BESS system architectures out of several MPT BESS topologies.

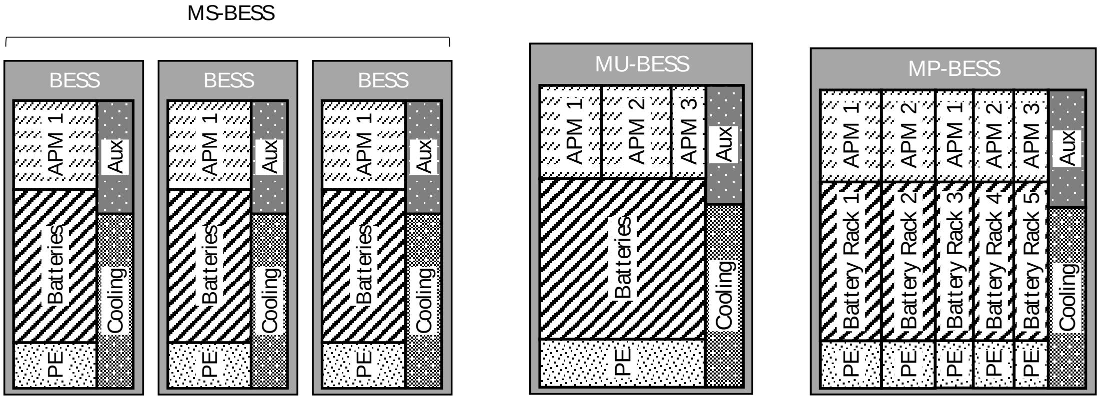

Figure 50 – Technical schematic of different BESSs. From left to right: i) Multi-Storage BESS (MS-BESS); ii) Multi-Use BESS (MU-BESS); and iii) Multi-Purpose BESS (MP-BESS).

The first example, multi-storage BESSs or swarm BESS (MS-BESSs), are MPT-BESSs that may consist of a series of grid connected single BESSs, of for example smaller BESSs ($< 15\ kWh$). Each singular system can be used for a local APM; however, they may share their non-utilized capacity for APMs, i.e., they are directed by central management. This capacity may include both power and energy capacity and even include utilized capacity; i.e. a fleet of BESS share energy capacity for providing SCR services in a community grid. This technology is known as virtual BESS or BESS swarms [199, 200]. MS-BESSs, in general, fulfil several APMs simultaneously by directing single BESS via an intelligent controller that acts as the man-in-the-middle communicator. Additionally, the given functionality of MS-BESSs can be divided into a single APM for different single systems or distributed over a combination of APMs among several regimes of BESSs; however, a single BESS may only operate a single APM at a time. If θ is a single APM for a single BESS then for each timestamp t the total power of the BESS swarm, $P_{MS-BESS}$, is given as follows:

$$P_{MS-BESS}(\mathrm{t}, \mathrm{n}) = \sum_{\theta=\mathrm{APM}_1}^{\mathrm{APMn}} P_\theta(t) \tag{24}$$

for n amount of APMs run on all MS-BESS. Thus, the swarm power always equals the sum of the individual power of the swarm participants; though each BESS may operate a different APM. Additionally, MS-BESSs can be part of an MS-BESS, i.e., a residential BESS provides the control reserve in a swarm while simultaneously following self-consumption optimization strategies, such as the Siemens subsidiary Caterva with 65 residential BESSs [201]. In an MS-BESS architecture, each system has a single cooling and auxiliary system component (Aux), which requires more parts than other system topologies with respect to the energy capacity.

The second example, multi-use BESSs (MU-BESSs), are single BESSs that serve multiple APMs with one specific power electronic unit at a time while dc-connected to a single battery capacity, which means that the system can output only one current at a time. The BESSs provide only one system-wide C-Rate for all of the APMs that are stacked onto it, e.g., an APM_1 with a C-Rate of 0.3 and an APM_2 with a C-Rate demand of 0.2 add up to a total C-Rate of 0.5 for the given single capacity. A separation of the capacity and proof of work are performed virtually due to the lack of single PE unites and distinct measurement points. MU-BESSs have a higher flexibility concerning the capacity assigned to specific APMs. MU-BESSs have only a single cooling and auxiliary system components (Aux), which requires fewer parts than other system topologies. Aux are typically additional system party, e.g. communication units, fault current sensors, monitoring units.

The third example, multi-purpose BESSs (MP-BESSs), are BESS which operates various PE units in different sizes, each with a single assigned battery capacity, i.e., a BR. The capacity allocated to a specific APM can be shifted incrementally based on the amount and size of the allocatable BR. An MP-BESS can serve multiple APMs simultaneously, which is comparable to MU-BESSs and MS-BESSs but can also provide physical evidence for proof of work because of the independent PEs per capacity, the same holds true for MS-BESS. MP-BESS offer several degrees of freedom, e.g., controlling the battery capacity, including charge and discharge currents (C-Rate), SOC and DOC manipulation per BR because independent PE is provided. Mathematically, MP-BESSs do not differ from MS-BESSs; however, MP-BESSs, which are mostly larger systems, i.e., a community BESS, combine the benefits of a single BESS unit outside and a decentralized swarm BESS inside. These include foremost the distinct proof of work measurement MS-BESS offers and the reduction of Aux system parts due to reduced complexity by using a single housing for several BESS a central larger BESS offers. Figure 50 depicts a basic technical schematic of the three different BESSs described.

In general, an MP-BESS is not able to directly provide more APMs than an MS-BESS or MU-BESS. However, superior APM fulfillment is possible because of the additional internal degrees of freedom; i.e. manipulation of c-rates across APMs on BESSs. However, this fact does not secure a positive economic value for such systems and does not include complete legal and legislative appraisals. Furthermore, MP-BESSs can operate each BR with a single EMS, which allows MP-BESSs to run BR separately irrespective of the APM and show a higher redundancy than MU-BESSs and MS-BESSs towards APM fulfillment; i.e. an MS-BESS single BESS cannot change an APM upon assignment where MP-BESS BR can switch or share APM assignment. A dedicated EMS provides the ability to manipulate the internal SOC, DOC, and C-Rate of the BESS per individual BR and PE. This reasoning leads to the assumption that an MP-BESS can, especially during times of low utilization, steer per BR DOC, mean SOC and other technical parameters and states, which leads to lower capacity fade; MS-BESS can utilize these degrees of freedom too, however, only are put under strong regulatory boundaries and may not yield the same positive outcomes MP-BESS are able to achieve.

Thus, MP-BESSs offer a slightly wider range for optimization, internal energy management and offer new approaches for a legal definition, which has yet to be defined by lawmakers and regulators. Table 21 provides a brief overview of the major differences between the above-mentioned system topologies. Partitioning a BESS into separately controllable BRs characterizes the technical peculiarity of the novel MP-BESS technology. For a better understanding of BESSs as MPT and a better description of the central issue of this work, Subchapter 5.2 details a case study that analyzed a BESS operating as MPT.

Table 21 – Basic characteristics of different configurations of BESSs considering legal, technical and economic factors for non-ideal BESS behavior.

		MP-BESS	MS-BESS	MU-BESS
Economical	Single APM	+	+	+
	Multi APM	+	+	+
	Independent PE	+	+	o
	APM wise proof of work with independent metering	+	+	o
Legal	Residential-based	o	+	+ / o
	Community-based	+	o	o
	Privately owned	+ / o	+	+ / o
	Third-party-owned	+	o	+ / o
Technical	Manipulation of			
	BR C-Rates per APM	+	o	-
	BR SOCs per APM	+	o	-
	BR DOCs per APM	+	o	-
	Different use battery technologies in one system	+	+	-
	Readiness for future APMs	+	+ / o	o

5.2 Simulation Model for MP-BESSs

The following material will describe the simulation environment and mathematical approach for the simulation and operation of an MP-BESS when stacking the APMs SELF, GRID, and SCP. This approach follows the operation strategy, legal framework and overall idea of the Energy Neighbor system as describe in the previous chapter.

As outlined in the Chapter 4.2 Excursus: The Simulation Environment – SimSES, all of the simulations regarding the MP-BESS in this thesis were performed using the SimSES tool as a whole, instancing the code structure to multiple objects and building an overlay simulation environment calling functions, objects and methods according to the necessary simulation step of the MP-BESS simulation. The following discussion will first outline the overall simulation approach and logical framework for a possible MP-BESS architecture simulation because there is a significant range of possible configurations for MP-BESSs, i.e., the presented technological structure is only one possible structure. Second, the simulation timeline and basic concepts will be explained, followed by the core functions that are necessary for the implementation of a community battery energy storage system (CES) under the given framework and market conditions as described in this thesis. Third, the results will be presented for an exemplary system. The MP-BESS system described in the following section is characterized by the technical data provided in Table 22. The chosen system was designed with a maximum power of 5.5 MW and an energy content of 5.5 MWh to legally participate in the market for SCP in Germany. The efficiencies and aging data were outlined in previous publications, specifically [137]. The LFP/C chemistry was chosen due to the mentioned benefits of this technology for BESS, see Subchapter 2.2.1. The price for the system was set based on the market-leader product offerings as of 08/2016. The aging scenario was optimistic, based on experimental data from [202], see Subchapter 2.2.1.

Table 22 – Data used to simulate an MP-BESS operating CES by stacking the APMs GRID, SELF, and SCP.

Name	Value	Unit
Usable energy capacity	5,500	kWh
Rated power	5,500	kW
Round trip efficiency (battery system only)	92.5	%
Battery chemistry	Lithium iron phosphate (LFP)	-
Calendar aging until 80% capacity	15	Years
Full cycles until 80% capacity	5,000	Cycles
Price	625[18] / 960[19]	EUR/kWh
Energy to power ratio of BR	1:1	-

The basic concept for MP-BESSs was described in 5.1, and the first results were shown in 5.2. Here, a brief description of the overall idea of a CES will be given. A CES, in general, is a possible substitution or addition in a grid area, mostly LV grids, in which a high penetration of RETs exists. Therefore, a CES combines the operation strategies of BESS in single households, which run individually, into a single entity. Instead of having several single home BESSs, a single BESS operating as CES works simultaneously for any connected load at the same grid level. (Refer to 4.1 for more details on the grid-level adaptability of BESS.) In contrast to single home BESSs and their utilization, it is possible to stack applications on CES to maximize its utilization and decrease the CAPEX and OPEX per stakeholder or investor. The simulated CES is a theoretical construct that can and will be freely divided into several sub-entities, as described in 5.1. The division into batteries, i.e., BRs, is expected to show the benefits for possible market tender, aging, and overall system cost. The simulated CES combines the APMs SELF, GRID, and SCP based on the detailed description and derivation in 5.2. The main challenge when operating such a BESS is to coordinate and conduct the power flow of BESS while maintaining full functionality per market and regulatory boundaries. To accomplish this goal, the CES is structured into several EMS layers, of which two are represented in the following simulation. The first is the interaction between the CES, and its environment of necessary power flows regarding the stacked applications, and the second is the interaction between BRs regarding optimal power and energy flows to minimize aging and optimize efficiencies. The following discussion will describe in detail all the necessary pre-simulations and boundaries and present a full simulation step to operate such a system.

[18] Low price scenario
[19] High price scenario

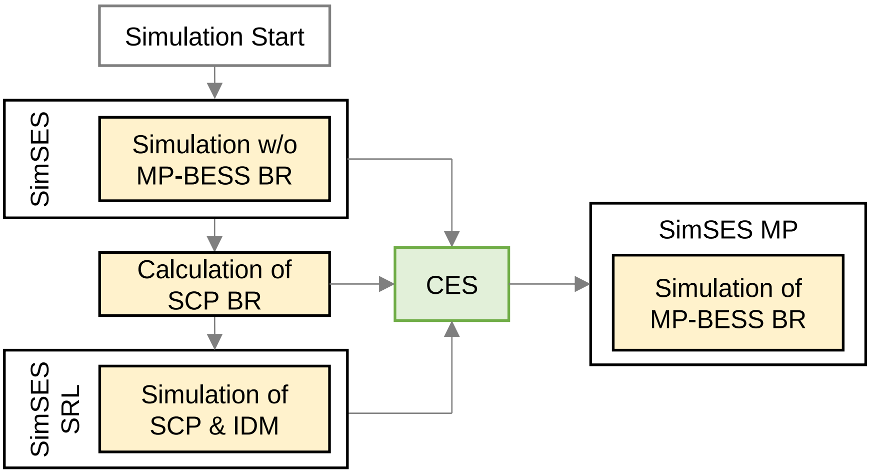

Figure 51 – Simulation pattern of the CES simulation.

Figure 51 depicts the overall function of the SimSES tool. In a three-step approach, the tool calculates the necessary load and power flows for the simple operation of the storage system to increase the communities self-consumption (Simulation w/o MP-BESS BR), the necessary load and power flows for participation in the secondary control reserve market (Calculation of SCP BR) and the necessary load and power flows for participation of the SCR BR in the intraday market (Simulation of SCP & IDM). After the calculation of each APM the storage system (CES) manages the different needs to serve the markets in an optimal way by calculating the best possible outcome per BR (Simulation of MP-BESS BR) for the period of one year.

5.2.1 Simulation without MP-BESS BR

The SimSES MP simulation computes the power flows P_{Res} and P_{Grid} utilizing SimSES and SimSES SRL, between solar generation P_{PV}, accumulated load of all grid connected consumers P_{load}, the battery power for community and grid service (CSG) BESS P_{CSG}, the intraday market participation power P_{idm}, and the power required by the SCP market P_{SCP} based on pre-simulations. CSG, in this case, is equal to the APM SELF+GRID introduced earlier. The following describes step-by-step the meaning and calculation of the aforementioned power flows.

$$P_{Res}(t) = P_{load}(t) - P_{PV}(t) * \eta_{PV} \tag{25}$$

$$P_{Grid}(t) = \left(P_{PV}(t) - P_{Load}(t) - P_{CSG}(t)\right) * \eta_{LPT} \tag{26}$$

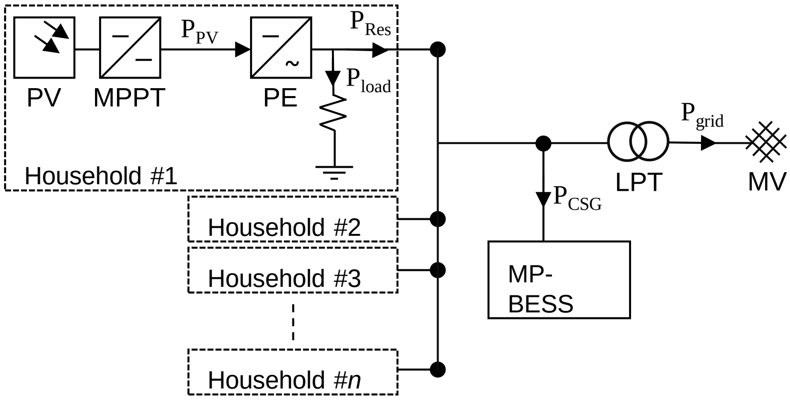

Figure 52 – Block diagram of several households connected to an LV grid with an MP-BESS operation in CSG APM as CES.

Figure 52 depicts the basic simulation setup of a series of households in an LV grid, which is comprised of a load and a PV system. Each household is connected to the public grid as well as the MP-BESS. Situated in the public grid, the MP-BESS can actively unload the local power transformer (LPT), i.e. by operation APM GRID. Let $C_{spare}(t)$ be the available storage capacity for each simulation step $t_{re}(t)$ be the predicted time until sundown and[20] be the maximum feed-in power $P_{feed-in_{max}}$. The power for CSG operation $P_{CSG}(t)$ is then either the quotient of the spare capacity C_{spare} and the remaining time until sunset t_{re}, but only for cases when the difference of the residual load P_{Res} and the maximum feed-in limit $P_{feed-in_{max}}$ is greater than or equal 0; or, $P_{CSG}(t)$ is the difference of the residual load P_{Res} and the maximum feed-in limit $P_{feed-in_{max}}$ when the difference of the residual load P_{Res} and the maximum feed-in limit $P_{feed-in_{max}}$ is less than 0.

$$P_{CSG}(t) = \begin{cases} \dfrac{C_{spare}(t)}{t_{re}(t)} \; \forall \, P_{Res} - P_{feed-in_{max}} \geq 0 \\ P_{Res} - P_{feed-in_{max}} \; \forall \, P_{Res} - P_{feed-in_{max}} < 0 \end{cases} \tag{27}$$

The necessary power for participation in the SCP market is based on the power price bid $p_{power}(t_w)$ per week in comparison to the SCP tender price $p_{act}(t_w)$ of each week (t_w). Therefore, to calculate the weekly SCP bid and necessary power P_{SCP}, a logical variable SCP_{act} functions as a flag to indicate provision of SCP during the simulation process and is set as a binary. The flag, weather SCP provision SCP_{act} is necessary for the upcoming week t_w, is set to 1 if the power price bid p_{power} for the same week t_w is less than or equal to the week's SCP tender price p_{act} and 0 if the power price bid exceeds all possible tender offerings for that week.

$$SCP_{act}(t_w) = \begin{cases} 1 \; if \; p_{power}(t_w) \leq p_{act}(t_w) \\ 0 \; if \; p_{power}(t_w) > p_{act}(t_w) \end{cases} \tag{28}$$

If a tender is won because of favorable bidding, the bids are set as simulation variables upon start of the simulation, then the maximum SCP power needed, $P_{SCP}(t)$, will be set to

[20] The maximum feed-in power $P_{feed-in_{max}}$ is limited due to restrictions by policies. Here this maximum is set to 60% of the installed PV peak power.

$$P_{SCP}(t) = \begin{cases} 0 \; if \; E_{off}(t_w) \lor \left(\mathrm{P}_{SCP}(t_w) \in \gamma(t_w)\right) \lor SCP_{act} = 0 \\ P \; if \; \mathrm{E}_{off}(t_w) \land \left(\mathrm{P}_{SCP}(t_w) \in \gamma(t_w)\right) \land SCP_{act} = 1 \end{cases} \tag{29}$$

for all energy prices $E_{off}(t_w)$ and power prices $\mathrm{P}_{SCP}(t_w)$ wining a bid in the merit order function γ described as $\gamma(t_w, n_{bids})$ for each week. Hence, the necessary power P_{SCP} for providing SCP is depended on the maximum energy bid by market participants, here the MP-BESS, and the resulting maximum power flows.

$$\gamma\,(t_w, n_{bids}) = \begin{pmatrix} \mathrm{E}_{off}(1) & P_{off}(1) \\ \vdots & \vdots \\ \mathrm{E}_{off}(n) & P_{off}(n) \end{pmatrix} with \; \mathrm{E}_{off}(1) < \; \mathrm{E}_{off}(2) < \; \mathrm{E}_{off}(n) \tag{30}$$

In every time step, the inverter efficiency (η_{inv}), battery round-trip efficiency (η_{Batt}), and capacity fading effects according to [26, 137] were considered. The time resolution for the simulation (Δt) is set to 1 min. The simulation was run for one year with one-minute time resolution to explicitly capture all the effects of an MP-BESS. Figure 51 depicts the simulation as a simple flow-chart. After the initial start of the simulation, all the necessary load and generation profiles for a simulation of a single BESS with the same technical data as the future CES were used to calculate APM demands and boundaries. When stacking APMs on a single BESS, an order of precedence for fulfilling certain APMs is necessary for the system to be able at any given time to serve all APMs. For instance, when prequalifying a BESS for x MW for the PCP provision, the underlying energy capacity and power reserve, regardless of the technical configuration, legally must remain the same over a complete period of service. Hence, if e.g. the APMs PCP and SELF were stacked, PCP must always remain the prior APM unless the power to energy ratio of PCP can change. For a CES, this requirement means that a precedence for APMs must be established, which in the outlined case follows the order of:

1. GRID
2. SELF
3. SCP

The order in this case is set by the necessity to unload the local power transformer with APM GRID at any given time during operation, followed by storing surplus energy with APM SELF and only with thereafter free capacity providing APM SCP. The simulation follows the first APM to stack, and the first APM is unloading of the local power transformer and the grid in the simulated area. The boundaries are two-directional dependencies. CSG influences the possible SCP ; however, the set SCP influences the possible CSG because of activation during low tariff on weekends and daytime. By implying a required dependence, the possible capacity for APM SCP can be formulated by dividing the total available CES capacity, $C_{Storage}$, subtracted from the CSG required capacity, C_{CSG}, by the total capacity per available subunit, C_{Rack}, a BR; see equation (36). This approach is achieved by constantly operating the CES with the feed-in damping operation strategy for SELF serving BESS. Additionally, the time of low utilization will be filled by APM SCP to increase the overall utilization of the CES. Therefore, as described earlier, the CSG simulation runs a single $5.5\ MW/5.5\ MWh$ BESS over the full simulation time, $t_{sim} = 1year$, and continuously calculates the necessary maximum share, $C_{CSG,Max}(t_d)$, of the CES capacity per day t_d to fulfil APM GRID + SELF each week and the capacity occurring at 8 AM, $C_{CSG_{8AM}}$, and 8 PM, $C_{CSG_{8PM}}$, for further calculations. A weekly partition is imperative in the regarded case because of the SCP tender times in Germany, which last for one full week.

$$C_{CSG_{8AM}} = C_{Storage} * SOC(\mathrm{t}_{8AM}) \tag{31}$$

$$C_{CSG_{8PM}} = C_{Storage} * SOC(\mathrm{t}_{8PM}) \tag{32}$$

$$C_{CSG,Max}(t_d) = \max\left(C_{CSG\ 8\ a.m.}(t_d), C_{CSG\ 8\ p.m.}(t_d)\right) \tag{33}$$

The yearly simulation data are sorted for each week and day, and the weekly maximum is selected; hence, the weekly performance of this model is depended on perfect forecast data for the upcoming week. The weekly maxima determine the necessary amount of CES capacity per week of the MP-BESS over the full simulation time to fulfill APM GRID + SELF every week. In the case, that all CSG BR are empty by e.g. 8 PM, all BR can be utilized for SCP provision.

$$\underline{C}_{CSGMax} = \begin{pmatrix} C_{CSGMax}\left(t_w(1), t_{w_d}(1)\right) & \cdots & C_{CSGMax}\left(t_w(52), t_{w_d}(1)\right) \\ \vdots & \ddots & \vdots \\ C_{CSGMax}\left(t_w(1), t_{w_d}(7)\right) & \cdots & C_{CSGMax}\left(t_w(52), t_{w_d}(7)\right) \end{pmatrix} \tag{34}$$

$$C_{CSGMax}\left(t_{w_d}\right) = \max\left(\underline{C}_{CSGMax}(t_w)\right) \forall\, t_w = 1,2,3 \ldots 52 \;\forall\, \mathrm{t}_{w_d} = 1,2 \ldots 7 \tag{35}$$

For a further increase in utilization, it is necessary to reflect on the SCP markets. The SCP market is divided into four tenders, which are HT+, NT+, HT- and NT- (see Subchapter 3.5 for more details). A MP-BESS, operating as CES, primarily serves the grid and the connected loads in the grid, i.e. APM GRID and SELF, which is dependent the daily cycle of RET, mainly PV power. The stacked secondary APM is negative SCP provision in NT, SNT-, i.e. charging of the MP-BESS SCP assigned BR during the night (8 PM – 8 AM). Thus, it is necessary to know how much energy each BR can additionally charge during the day (8 AM – 8 PM). Generally speaking SCP BR should operate as CSG BR during HT, and as SCP BR during NT. Therefore, any SCP assigned BR has to be empty by both HT/NT switch times, 8 AM and 8 PM. In other words, the energy of all SCP assigned BRs can charge per day, $E_{SCRMax}(d)$ and still provide full capacity at 8 PM when HT/NT switches, and the full prequalified SCP power. The energy all SCP assigned BRs are able to store during HT of a given day is given boundary that all SCP BR must be empty by 8 PM. All additional energy, E_{SCPMax}, can be added up to give the minimal necessary capacity, $C_{CSG_{max}}$, and provide a MP-BESS primary APMs over a day. Using a defined capacity for each BR, C_{BR}, the total number of possible SCP providing BR $n_{BR_{SCP}}$ during low tariff can be calculated as follows:

$$n_{BR_{SCP}}(t_w) = \left\lceil \frac{C_{Storage} - C_{CSG_{max}}(t_w)}{C_{Rack}} \right\rceil \tag{36}$$

and the maximum available power, $(P_{SCP,max})$, for providing SCP during low tariff is

$$P_{SCP_{max}}(t_w) = \sum_{1}^{n_{SCP}(t_w)} P_{BR,\mathrm{n}} \tag{37}$$

Figure 53 shows the distribution of CSG and SCP BR over the simulation time of one year for the given MP-BESS operating as CES based on the given criteria for distributing APMs CSG and SCP on BRs.

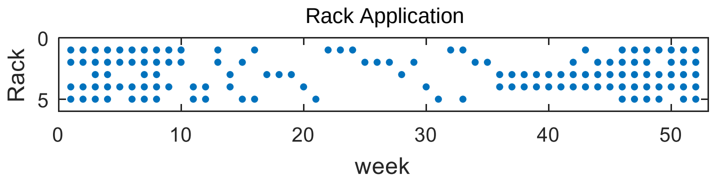

Figure 53 – Exemplary distribution of CSG and SCP BR over a one-year simulation for an MP-BESS operating as CES with five BRs. Blue dot = SCP BR; no dot = CSG BR.

After the pre-simulation for the CSG operation was outlined, the maximum capacity available for SCP provision within the boundaries of CSG operation optimization during HT periods was used. The following shows the calculation methods used to estimate the required power flow for a shared CSG and SCP operation in a single BESS. The tariff, HT or NT, in which a CES operates in is decisive for mixed operation. The maximum power outputs or inputs are limited to the maximum outputs and inputs of power electronics. For the HT operation, the output vector of the required CSG power $P_{CSG}(t)$ and required SCP power $P_{SCP}(t)$, to fulfill the operation strategies demand must, be calculated for three different cases; see Subchapter 5.2.2. For NT operation see Subchapter 5.2.3.

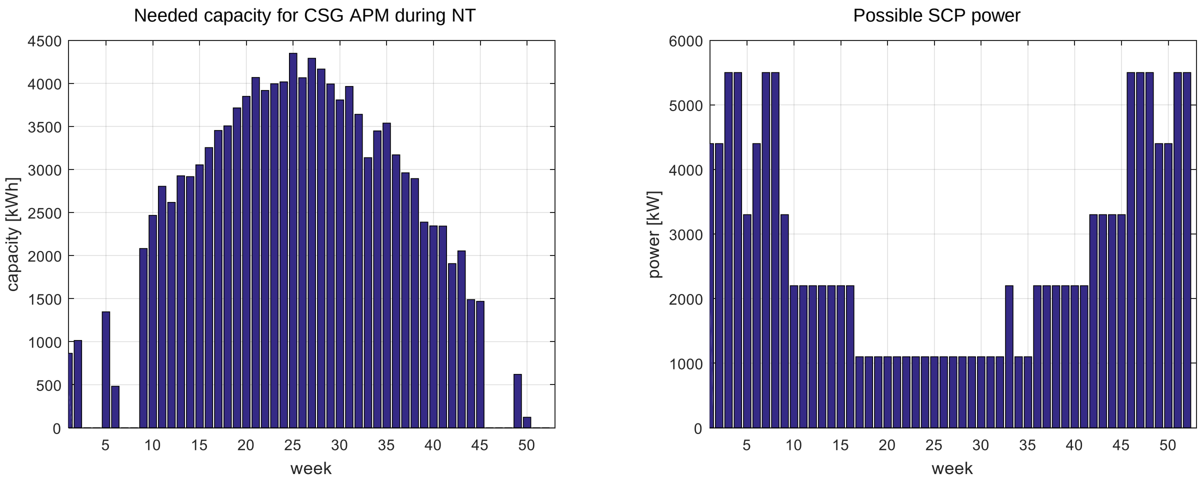

Figure 54 – Visualization of the dependencies between CSG and SCP APM on a CES.

Figure 54 depicts the dependencies between the APM CSG and SCP on a CES MP-BESS. Whenever there is a lack of utilization due to CSG, SCP as a secondary APM is increased. In addition to the technical positive outcomes, this behavior leads to an increase in possible tenders as well, which will ultimately have a positive influence on the economics of an MP-BESS. For a better understanding at the end of this subchapter Figure 55 shows in detail an MP-BESS working under the following high and low tariff operation strategies APM CSG and SCP for a 24 hours simulation period.

5.2.2 Case distinction for high tariff operation

A further understanding and explanation of the method operating an MP-BESS require a case distinction for three specific operation states of the MP-BESS:

1. CSG BR being charged; no IDM trading; if $P_{CSG\ lim}$ is exceeded SCP BR should be charged.

$$P_{CSG_{lim}}(t) \geq 0 \,;\, P_{IDM}(t) = 0 \tag{38}$$

2. CSG BR being discharged; no IDM trading; SCP BR should always be discharged prior to CSG BR for SCP readiness at the start of LT.

$$P_{CSG_{lim}}(t) < 0\,;\ P_{IDM}(t) = 0 \tag{39}$$

3. CSG BR are being either discharged or charged; IDM trading active for SCP management; SCP BR are disclosed for use in CSG APM

$$P_{IDM}(t) \neq 0 \tag{40}$$

which are outlined in the following. All calculations must be within the SOC limits:

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{41}$$

5.2.2.1 Case 1 – Charging the MP-BESS without IDM trading

In the case that all the CSG BR will be charged (and only charged), $P_{CSG}\ (t) > 0$, there is either no need or no legal opportunity for IDM trading, $P_{IDM}(t) = 0$, the SOCs follows

$$SOC_{CSG}(t) = \frac{\eta_{BESS}\ *\ P_{CSG_{lim}}(t)}{C_{CSG}(t)} *\ \Delta t + SOC_{CSG}\,(\mathrm{t}-1) \tag{42}$$

under the constraints that the overall storage CSG power $P_{Stor_{CSG}}$ is not exceeding the maximum possible power per BR in assigned APM CSG following

$$\left|P_{Stor_{CSG}}\right| \leq \sum_{1}^{n_{CSG}} P_{BR_{CSG,n}} \tag{43}$$

In the case of a difference between CSG power P_{CSG} and the limited CSG power $P_{CSG_{lim}}$ all SCP BRs will start working as follows, i.e. the APMs GRID or SELF require more power than CSG BR can provide, SCP BR will start working preventing the system from violating prerequisites for CSG operation.

$$P_{SCP}(t) = \begin{cases} 0\ \forall\ P_{CSG_{lim}}\,(t) \geq P_{CSG} \\ P_{CSG_{lim}}\,(t) -\ P_{CSG}(t)\ \forall\ P_{CSG_{lim}}(t) < P_{CSG}(t) \end{cases} \tag{44}$$

In the case, that $P_{CSG}(t)\ \leq P_{CSG_{lim}}$ hence, the required power is within the limits and no additional power by SCP BR is necessary. In the case, that $P_{CSG}(t)\ > P_{CSG_{lim}}$ the overloading power is distributed amongst SCP BRs by calculating new SOCs of the SCP BRs

$$\begin{aligned} \Delta SOC_{SCP} &= \frac{\eta_{BESS} * P_{SCP}(t) *\ \Delta t}{C_{SCP}(t)} \\ SOC_{SCP_{new}}(t) &= \Delta SOC_{SCP}(t) + SOC_{SCP}\,(t-1) \end{aligned} \tag{45}$$

under the constraints of power limitations per SCP BR to $P_{SCP}(t)$ following equation

$$\left|P_{Stor_{CSG}}\right| \leq \sum_{\mathrm{i}=1}^{n_{SCP}} P_{BR_{SCP,\mathrm{i}}} \tag{46}$$

$$P_{SCP}(t) = P_{CSG_{lim}}\,(t) -\ P_{CSG}(t) \tag{47}$$

The described behavior is depicted in Figure 55 and can be seen at around 15:30 when the grid power increases to such extents, due to a rapid increase in feed-in power from RESs, the fifth BR of that MP-BESS, which is operating CSG+SCP, starts charging immediately until the power requirement is covered at 16:30. At that time the same BR starts discharging due to the distinct case 2 describe in the following subchapter.

5.2.2.2 Case 2 – Discharging the MP-BESS without IDM trading

For the case that all CSG BR are discharging (and only discharging) $P_{CSG}(t) < 0$, there is either no need or no legal opportunity for IDM trading $P_{IDM}(t) = 0$ SCP BRs must be discharged always first in order to guarantee empty SCP BRs when the switch between HT/NT occurs. The SOCs for SCP BRs follows

$$SOC_{SCP}(t) = \frac{\eta_{BESS} * P_{CSG_{lim}}(t)}{C_{SCP}(t)} * \Delta t + SOC_{\text{SCP}}(\text{t} - 1) \tag{48}$$

under the constraints that the overall storage SCP power $P_{Stor_{SCP}}$ is not exceeding the maximum possible power per BR in assigned APM CSG following

$$|P_{Stor_{SCP}}| \leq \sum_{1}^{n_{SCP}} P_{BR_{SCP,n}} \tag{49}$$

Hence, SCP BRs provide any required CSG power unless they are empty. However, if a difference is recognized between the overall SCP power $P_{Stor_{SCP}}$ and the SCP power limit $P_{SCP_{lim}}$, all CSG BRs will start working to relieve overloading of SCP BRs according to

$$P_{CSG}(t) = \begin{cases} 0 \;\forall\; P_{SCP_{lim}}(t) \geq P_{Stor_{SCP}}(t) \\ \left(P_{Stor_{SCP}}(t) - P_{CSG_{lim}}(t)\right) \;\forall\; P_{SCP_{lim}}(t) < P_{Stor_{SCP}}(t) \end{cases} \tag{50}$$

In the case, that $P_{SCP}(t) \leq P_{SCP_{lim}}$ hence, the required power is within the limits and no additional power by SCP BR is necessary. In the case, that $P_{SCP}(t) > P_{SCP_{lim}}$the overloading power is distributed amongst CSG BRs by calculating the new SOCs of the CSG BRs by

$$SOC_{CSG}(t) = \frac{\eta_{BESS} * P_{CSG}(t)}{C_{CSG}(t)} * \Delta t + SOC_{CSG}(\text{t} - 1) \tag{51}$$

under the constraints of power limitations per CSG BR to $P_{CSG}(t)$ following equation

$$|P_{Stor_{CSG}}| \leq \sum_{1}^{n} P_{BR_{CSG,n}} \;\forall\; n\; CSG_{BR} \tag{52}$$

$$P_{CSG}(t) = P_{SCP_{lim}}(t) - P_{SCP}(t) \tag{53}$$

The describe behavior is depicted in Figure 55 and can be seen at around 16:30 when the grid power decreases below 0, due to a decrease in feed-in power from RESs, the fifth BR of that MP-BESS, which is operating CSG+SCP, starts discharging immediately until it is completely empty at 17:40. At that time, the first BR, operating CSG only, start discharging and covering the grid load.

5.2.2.3 Case 3 – Dis-/charging and IDM trading

For the case that CSG BRs are discharged or charged, and SCP BRs simultaneously participate in the IDM market, the boundary condition is that SCP BRs in that state are unavailable for CSG operation. CSG BR follow the demanded power until $P_{CSG_{lim}}$ is reached. The SOCs follows (for charging or discharging) the same calculation as stated in case 1 under similar limitations of the maximum possible output power for CSG operation based on the number of assigned CSG BR and their power electronics limitations.

$$\left|P_{Stor_{CSG}}\right| \leq \sum_{\mathrm{i=1}}^{n_{CSG}} P_{BR_{CSG,max}} \tag{54}$$

While the power of SCP BR simply follows

$$P_{Stor_{SCP}}(t) = P_{SCP}(t) + P_{IDM}(t) \tag{55}$$

because any limitations have been calculated previously for the SCP simulation.

These results are valid only for HT tariff times. However, low tariff operation is similar to HT operation and can be described for the three cases mentioned prior. The describe behavior is depicted in Figure 55 and can be seen in the period from 00:00 until 08:00 and 20:00 until 00:00 the next day. During the given period the fifth BR provides SCP by charging upon SCP demand and immediately, as soon as possible, selling the charged energy at the intra-day market.

5.2.3 Case distinction for low tariff operation

First, for $\boldsymbol{P_{CSG}\,(t) \geq 0}$; $\boldsymbol{P_{IDM}(t) = 0}$; $\boldsymbol{P_{SCP}(t) = 0}$, none of the assigned SCP BR can assist CSG functionality because the SCP demand is imminent at any given time.

Second, for $\boldsymbol{P_{CSG}\,(t) < 0}$; $\boldsymbol{P_{IDM}(t) = 0}$; $\boldsymbol{P_{SCP}(t) = 0}$, any discharge of SCP BR, to assist CSG BR, is legally prohibited, and SCP energy must be sold at the IDM market.

Third, for $\boldsymbol{P_{SCP}(t) \neq 0 \; or \; P_{IDM}(t) \neq 0}$, the storage output follows

$$P_{SCP}(t) = P_{SCP}(t) + P_{IDM}(t) \tag{56}$$

The simulation has shown that all the necessary profiles and vectors for operating a BESS as an MP-BESS, specifically a CES BESS, were calculated. From a critical point of view, this operation strategy could be implemented without relying on BRs, which was calculated in the simulation and will be shown in the results. The resulting power per APM, i.e., $P_{Stor_{SCP}}(t)$, as the vector of total SCP power in kW over the simulation time, as well as, $P_{Stor_{CSG}}(t)$, can be distributed, e.g. , equally over all available BRs. An equal distribution of power follows

$$\begin{gathered}
BR_{Share_{CSG}}(t) = \frac{P_{Stor_{CSG}}}{\sum_1^n P_{BR_{CSG}}} \;\forall\, n\; CSG_{\mathrm{BR}} \\
P_{CSG_{BR,n}}(t) = BR_{Share_{CSG}}(n,t) * P_{Stor_{CSG}}(t) \\
BR_{share_{SCP}}(t) = \frac{P_{Stor_{SCP}}}{\sum_1^n P_{BR_{SCP}}} \;\forall\, n\; SCP_{\mathrm{BR}} \\
P_{SCP_{BR,n}}(t) = BR_{share_{SCP}}(n,t) * P_{Stor_{SCP}}(t)
\end{gathered} \tag{57}$$

Concluding the MP-BESS simulation, the SimSES core is utilized to simulate each BR per the APM and any preset technical data.[21] The SimSES core will update the respective BR object and handle all technical data for each simulation step. However, the above approach distributes the overall power equally over all available BRs, which leads to PE operation at low efficiencies and a lower BESS economic value. Subchapter 5.5 will introduce some optimization approaches. In addition to power selecting BRs, BRs can switch their respective APM on a weekly basis to optimize the functionality of the CES.

[21] For future work, the CES tool can freely access BRs of different sizes, power electronics, and aging mechanisms, among other parameters.

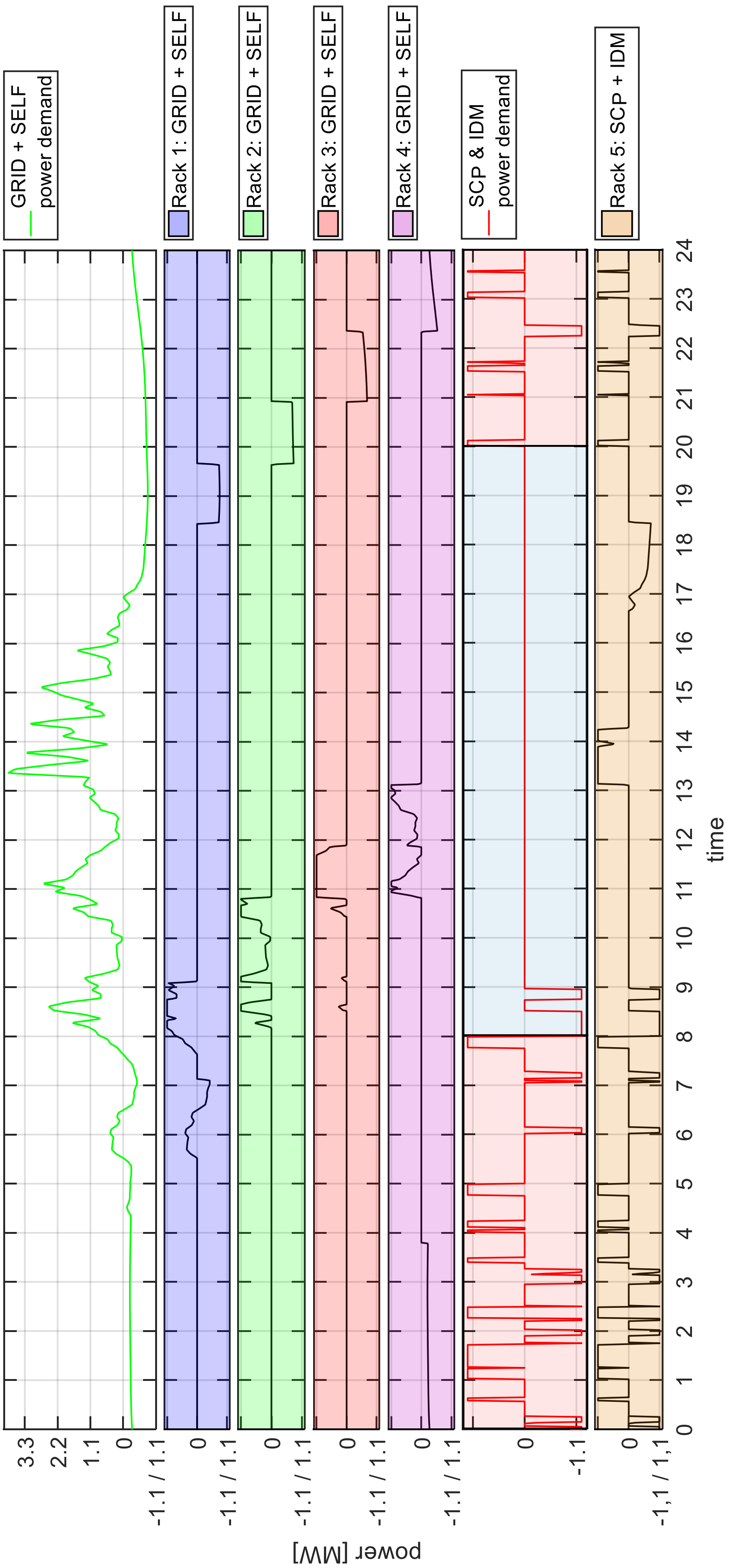

Figure 55 – Depiction of a 5.5 MWh / 5.5 MW MP-BESS a 24 hour period with 5 BRs of which four (BR 1 to 4) are operating APM CSG and one BR (BR 5) APM SCP/IDM (NT) + CSG (HT). (SCP & IDM plot – blue area HT, red area NT).

5.3 Multiple Use of BESSs

Subchapter 5.1 introduced the idea and concept for driving an SPT BESS toward MPT-BESS. BESSs can, from a technical perspective, serve several APMs simultaneously. Additionally, BESSs can technically serve several APMs independently of the time or under time-shifting of the APMs per timeframe. Subchapter 4.3 showed that BESSs could operate on different grid voltage levels and in a variety of conceptual setups with possible economic value for APMs (see Subchapter 2.3 and Chapter 3). The following subchapter will further analyze additional reasons for operating BESSs as MPT rather than SPT. The differences in operational strategies for a single APM and the differences and concepts for an MP-BESS will be explained.

5.3.1 On the multiple uses of BESSs

In general, economic principles indicate that the utilization rate, i.e., capacity utilization or capacity factor, is the ratio between the output of a machine/firm/person and the maximum work that can be performed per time unit. In other words, the utilization ratio measures the ratio between the total possible time of utilization, T_{ref}, and the standby time of a firm/machine, $T_{BESS_{unused}}$. Based on these conclusions, BESS operation in an LV grid with an APM GRID[22] (See Subchapter 4.3) shows a utilization rate of $r_u = 1.64\%$ [92] which follows:

$$r_u = \frac{T_{BESS_{operation}}}{\mathrm{T}_{total}} \tag{58}$$

A BESS operating in an APM GRID can limit the real power of an LV transformer. Figure 36 shows transformer stations from the KWH Netz grid; the implementation of an LV BESS would be suitable to limit the transformer station's power, which, in many cases, is under overload because of heavy RET installations in the LV grid.

Connecting a BESS in LV grids close to the RET systems improved both the grid voltage and transformer load significantly; see Figure 17. Figure 56 shows the daily usage of the BESS operating in the APM GRID in the top-left graph. Fundamentally, the previously mentioned economic principles and outlined thoughts (see Subchapter 1.2 and 5.1) lead to the necessity of increasing the BESS overall utilization ratio. This increase can be achieved by either changing the APM or adding more APMs to supplement the existing APM GRID. Aside from the APM GRID, a common APM for BESSs is storing RET surplus energy, which is called APM SELF[22]. "PV system operators can temporarily store their surplus energy for using it whenever necessary […]" [92] using BESSs in LV grids as residential home storage. This situation holds true for larger-scale BESSs in LV grids as well, as [203] shows. The single operation of APM SELF under the given simulation environment leads to a utilization ratio of 25.92% [92]; refer to Figure 56 top-right for a detailed daily analysis. Apart from APM SELF, operating under the constraints of Equation (6) (p.40), APM SELF can be applied in a grid-friendly way. When operating a BESS with APM GRID + SELF, a utilization ratio of 30.63% [92] is obtained. (Refer to Figure 56 bottom-left for a detailed daily analysis.) An assumed increase in the utilization ratio of the storage is observed, but the operational times in winter naturally lead to a relatively low utilization ratio because of the lower insolation rates during the daytime.

[22] See Table 7 (p. 27) for abbreviation and APM explanation.

At this point, the two APMs, SELF and GRID, were combined to achieve a higher utilization ratio. The economic value of the BESS could be simultaneously increased by the value a DSO is willing to pay for transformer unloading. A BESS operating simultaneously under APM SELF and GRID mostly operates during the daytime. A BESS will start charging at sunrise as soon as the PV power exceeds the grid load and it always limits the maximum transformer load by operating under a grid-friendly operation strategy (see Subchapter 3.7). In the early evening hours, mostly before midnight, the stored energy will be completely discharged, and there is no use for the BESS during the night. Figure 56 shows the BESS behavior under the previously explained APM scenarios. There are several options for using BESSs during the night that can be investigated, including the provision of negative SCP during low tariff in the case of German regulation.

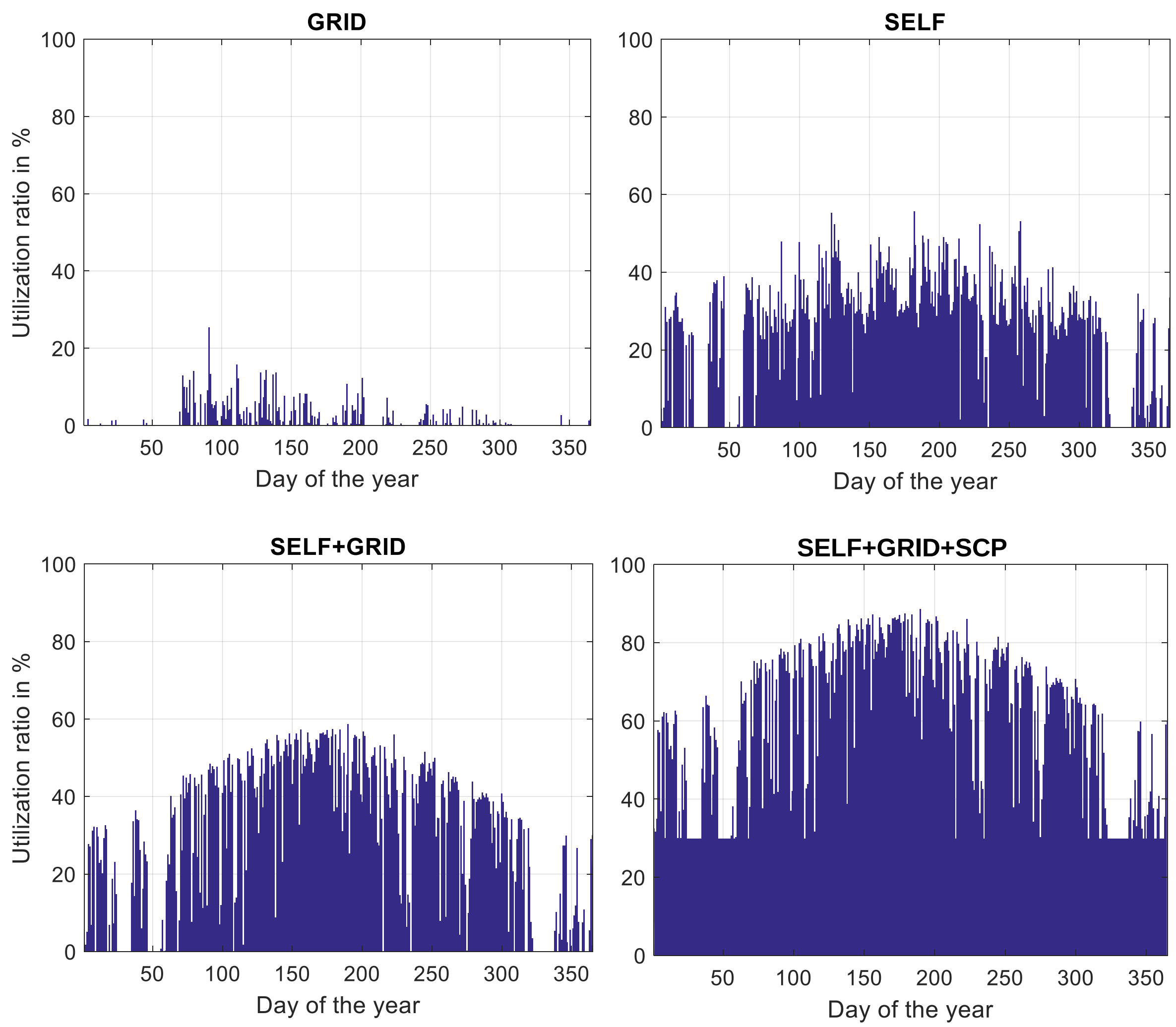

Figure 56 – Daily utilization ratio for a BESS reducing the grid load (top left), storing PV surplus energy (top right), operating in a grid-friendly manner by storing PV surplus energy (bottom left) and providing SCP while storing PV surplus energy (bottom right). [117]

By adding APM negative SCP during low tariff, the utilization ratio for the same BESS increases to 61.86% [92], which is depicted in the bottom right of Figure 56. Specifics on how to operate such a system and the simulation method are given in Subchapter 5.2. In summary, BESSs are suitable to operate as MPT in LV grids and other grid levels because there are combinations of

APMs that do not exceed BESS physical boundaries. In spite of the variety of imaginable methods for the operation of an MP-BESS, there are certain criteria that must be fulfilled and processed to develop a fundamental method for the multi-tasking operation of BESSs. The following section introduces an operational concept and guidelines for the operation of an MP-BESS in LV grids under the assumption that the aforementioned three APMs are run simultaneously (SELF, GRID, and negative SCP during low tariff).

5.3.2 On the operation of a multi-tasking BESS

The concept of storage fragmentation, i.e., splitting up a BESS into several independent BRs to operate individual PE, was mentioned briefly in Subchapter 2.2. The necessary technical functionality MP-BESSs required for running multiple APMs will be introduced along with the simple control algorithm steering the system. The following results have been published in the co-authored publication, "Operating a Multitasking Stationary Battery Storage System for Providing Secondary Control Reserve on Low-Voltage Level" [92]. As Subchapter 2.2 explained, the general concepts for allowing BESSs to work as MPT (see Subchapter 1.2 for MPT and SPT explanations) and conceptual ideas for operating an MP-BESS in an LV grid are derived in the following section. The operation of a BESS from single APMs toward stacked APMs as MP-BESSs will be described for an LV MP-BESS.

The Energy Neighbor (EN), an MP-BESS prototype that was built under the auspices of the EEBatt project at TUM, consists of eight BRs with a total capacity of $C_{max_{EN}} = 191.36\ kWh$ and a total power of $P_{max_{EN}} = 248\ kW$. The full technical data in Table 2 and further explanations of the technical components in Subchapter 2.2 are available. The EN operates eight BRs, each with an independent PE unit P_{BR_n} and capacity C_{BR_n}, in the 400 VAC LV grid.

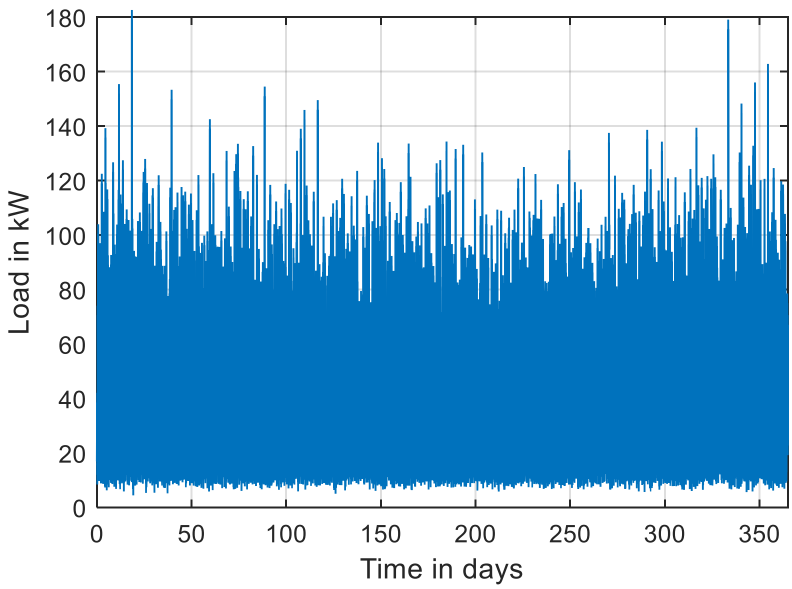

Figure 57 – Accumulated load profile of the grid area under investigation [92].

The following results were simulated by targeting a small LV grid referring to the EEBatt projects' EN (see Subchapter 1.2 for further information on the prototype system). "*The operated grid consists of three branches with several short leavings, all connected to a transformer with a* *rated power of 250 kVA*" [92]. With 50 households and 18 PV systems, an overall maximum solar generation power of 261.6 kW is assumed under the constraints of a simultaneity factor of 0.85 [116]. See Figure 59 for the grid's structure and Figure 57 for the accumulated load profile. The simultaneity factor describes the variety of the PV system installation, i.e., horizontal and vertical angle to the sun and daytime differences in the total insolation. For realistic load and solar production rates and profiles, statistically generated profiles were fit individually to each of the 50 households, which is depicted in Figure 58 [204].

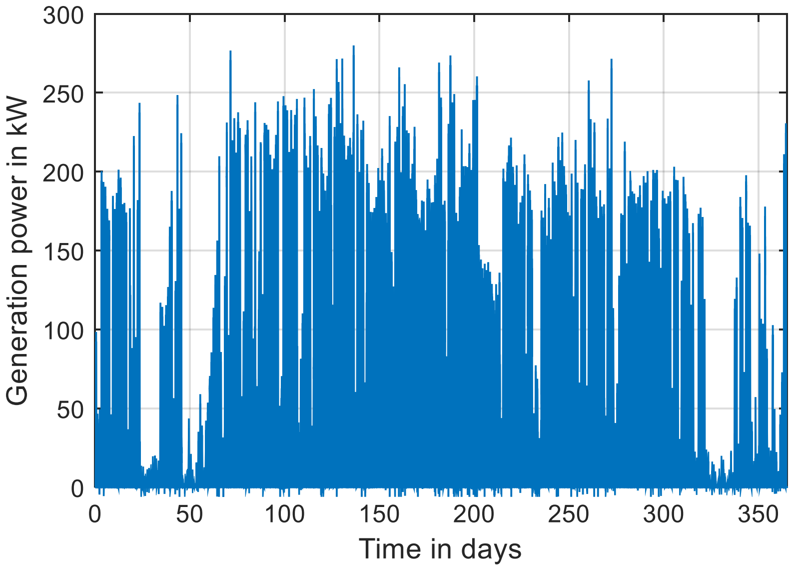

Figure 58 – Accumulated generation profile of the grid area [92].

When operating an MP-BESS certain APMs such as SCP require proof of work. As described before, the provision of control power, e.g., SCP, requires specific evidence in form of dedicated measurements of metering devices, mostly in the form of a smart meter or bi-directional measurements in the market. These measurements often cannot be calculated from the overall BESS behavior or PE performance, but they must rely on measuring devices connected directly to the BRs serving different APMs. However, this capability can be realized in the near future when the measurement precision increases and the legal framework allows for inter-storage power flow measuring to prove work.

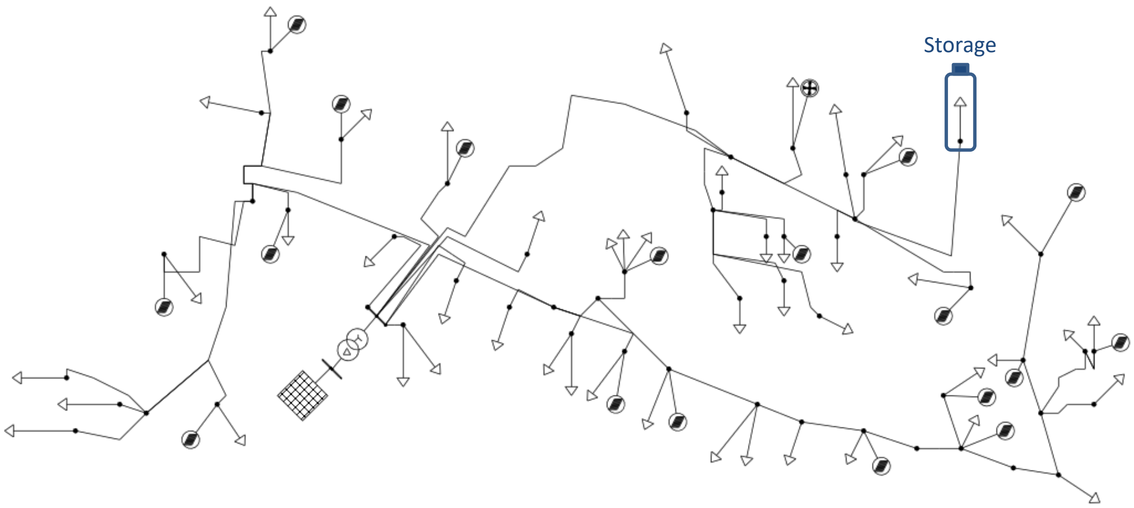

Figure 59 – Sketch of the case-studied grid "Moosham" with installed BESS [39].

When providing SCP, i.e., negative SCP in the LT, a proof-of-work operation can be performed by measuring the BRs energy that are assigned to this APM. Therefore, in times of operating SCP, it is prohibited to operate the BR for other APMs. A calculation of the maximum awaited energy E_{max} during switching times of low tariff to HT, based on weather and load profile forecasts, leads to the possible number of BR, $n_{BR_{SCP}}$, for operating SCP in parallel to GRID+SELF. In the outlined case, $n_{BR_{SCP}} = 5$ can serve negative SCP in low tariff based on the following equation, where $E_{BR_{EN}}$ represents the capacity of each BR assuming that all BR have an equal capacity:

$$n_{BR_{SCP}} = \left\lfloor \frac{E_{EN} - \mathrm{E}_{max}}{E_{BR_{EN}}} \right\rfloor \tag{59}$$

Separating BRs is necessary to avoid clashes of APMs and to provide physical evidence for work proofs; otherwise, the MP-BESS could serve multiple tasks virtually without exchanging power with the grid. For example, an MP-BESS could sell the exact same amount of energy on IDM and provide SCR by charging the system, which would lead to zero power flow but gaining in two markets. Operation algorithms for an MP-BESS relieving the grid and transformers from overload is a control algorithm similar to the greedy operation of an MP-BESS and are expressed as follows:

$$P_{load}(\mathrm{t}) > P_{th}(\mathrm{t}) \rightarrow P_{ch}(\mathrm{t}) = P_{th}(\mathrm{t}) - P_{load}(t) \tag{60}$$

$$P_{load}(\mathrm{t}) > P_{PV}(\mathrm{t}) \rightarrow P_{dch}(\mathrm{t}) = P_{load}(\mathrm{t}) \tag{61}$$

When the transformer load, P_{trans}, exceeds the thermal threshold power of the transformer P_{th}, the grids' installed MP-BESS starts to charge with the amount of overcharging power, P_{ch} and relieves the grid. Figure 60, top left, depicts this behavior. In times when the grid load is greater than the amount of available RET energy in the grid, the MP-BESS will start discharging with, $P_{dch}(\mathrm{t})$. Figure 60, top right, shows the greedy operation OS serving APM SELF. The MP-BESS is fully charged by 9 AM and further operation, i.e., relieving the grid, is not possible. To combine the APMs SELF and GRID, shown in [117] and [205], the BESS follows the same logic as equation (60); however, the MP-BESS charging power, P_{ch}, is now calculated as shown in equation (17).

Applying the newly defined charging behavior, the storage never charges with its full power but with the calculated necessary power at each time step, t, to reach an SOC of 100% by sunset. The discharging behavior follows the same logic as before, and this MP-BESS behavior is depicted in Figure 60, bottom left.

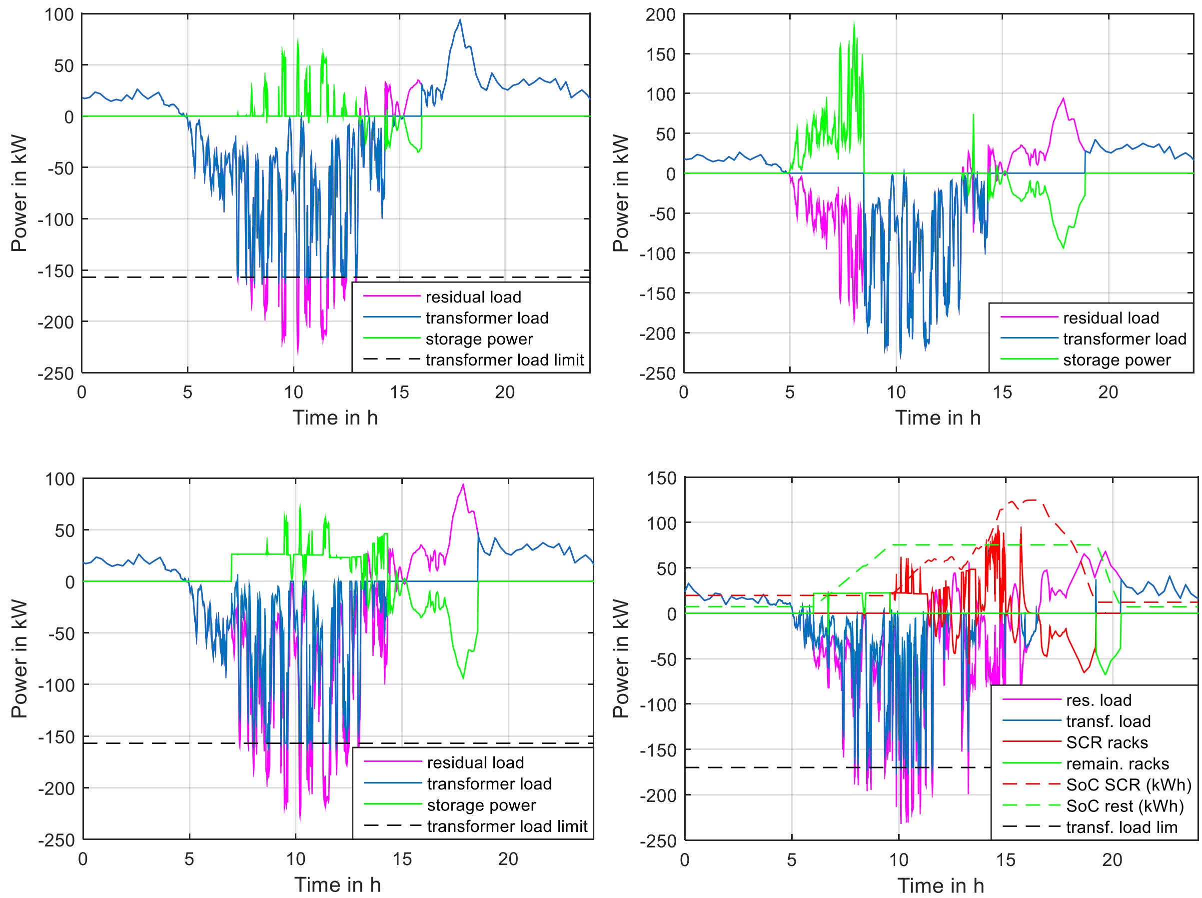

Figure 60 – Load curves and cumulated storage power of a MP-BESS over 24 hours of an exemplary day under different APMs; reducing grid load (top left), storing PV surplus energy (top right), grid-friendly operation storing PV surplus energy (bottom left) and providing SCP while storing PV surplus energy on a business day (bottom right). [92].

Adding the APM SCP to the previously shown results produces the MP-BESS behavior depicted in Figure 60, bottom right. This figure shows, in addition to the different MP-BESS and BR powers, the SOCs for both the SCP reserved BRs and the remaining BRs serving SELF+GRID APM. The logic for the operation of an MP-BESS for SELF+GRID+SCP as APM is mainly governed by the market design and rules for providing SCP. Under the assumption of German regulations, there is an low tariff phase from 8 PM until 8 AM and an HT phase from 8 AM until 8 PM. The different tariff is important because SCP can be sold in either/both positive or negative configurations for the given timeframes. The analysis concludes that selling negative SCP in LT is most suitable and should served by an MP-BESS. In other words, the MP-BESS can be charged when grid operators trigger negative SCP signals during low tariff with additional power because the APMs SELF + GRID operate exclusively during the daytime.

This behavior leads to charging the MP-BESS during the night and on weekend days, which equal the low tariff period. In reference to Figure 60, the BESS starts to relieve the grid according to APM GRID + SELF and stores RET power during the overload/threshold times of the transformer station. At 10 AM, the BESS SOC for non-SCP BR reaches 100% (75 kWh), which results in a conflict of operation for the APM grid. While APM SELF would at this point not require further charging, the SCP reserved BRs are activated to take over and ensure the continuation of the MP-BESS main function. In contrast, the discharging behavior aims at discharging SCP reserved BRs first to provide negative SCP after 8 PM in the low tariff period. In other words, SCPs must be fully discharged by 8 PM[23]; if the grid load is not sufficient to discharge all SCP BR and the surplus energy is sold at the latest possible IDM tender. Therefore, at 1 PM and 4 PM, the SOC of SCP BR declines because SCP BR serves any grid load directly. The remaining BRs remain at 100% SOC until 7 PM when all the SCP BR have been discharged and start discharging then by serving grid load. The BESS is now able to provide negative SCP during the low tariff period.

In summary, the operation of an MP-BESS relies widely on the technical setup of the storage system itself, regulations according to proof of work for APMs and the logic of stacking APMs. "*Operating a multitasking storage for reducing the grid load, storing PV surplus energy and providing secondary control reserve on LV level can distinctly increase the utilization ratio of the system compared to a single-tasking application. Especially the provision of negative SCP […] is feasible for the usage of inactive storage capacity. Nevertheless, the maximum amount of SCP power to be provided strongly depends on the existent grid infrastructure and given targets for reducing the grid load and has to be individually determined for every grid.*" [92] This short outline serves to provide a basic understanding for stacked APMs on an MP-BESS. A detailed analysis of MP-BESS behavior, the algorithms providing the features for controlling MP-BESSs serving three APMs, and the fundamentals of APM stacking were provided in Chapter 4.8.

5.4 Influence of APM Stacking on Aging

Aging of LIB cells is the leading cause of a limited lifetime for BESSs and electric vehicle batteries. The following results on the influence of APM stacking on the aging of an MP-BESS were published as "Evaluation of the Aging Behaviour of Stationary LIB Storage Systems for Different PV-Driven Applications in Low Voltage Grids" [206].

In general, battery degradation causes can be separated into calendar aging and cycle aging [52, 207–209]. Aging degradations are changes inside the LIB cell, e.g., increased SEI layer growth, caused by varying stress factors. Calendar aging considers the stress factors of BESS within a specific SOC and temperature over time. Cycle aging takes the charging and discharging processes into account [207, 208]. In the literature, numerous studies show the impact of stress factors, such as the current, ΔSOC, SOC and temperature to cell capacity, and impedance parameters, such as the internal resistance [52, 210–212]. In [213], the impact of

[23] The results in Figure 60 show that (bottom-right) SCP BR still maintain around 10% SOC after 8PM. This is caused by a hard programmed discharge of 10% SOC to asses aging effects.

SOC and temperature on the capacity fade and resistance increase was investigated for NMC Sanyo UR 18650E cells. The cells stored at lower SOCs exhibited a longer life. In particular, the cells stored at 100% SOC showed a much faster degradation rate than the other cells.

In addition, Marongiu et al. [214] came to the conclusion that cycling around the nominal voltage leads to the lowest increase in the inner resistance and decrease in capacity for the LIB cell. From a calendar aging standpoint, high temperatures and high SOCs should be avoided, and cycling around the middle voltage is beneficial. Apart from calendar aging, the charging and discharging current is a stress factor for cycle aging. As reported by several studies, cycling of batteries at high C-Rates leads to faster degradation of the batteries [215–217]. The mentioned SOC level is highly influenced by the APM of a BESS. The APM PCP and SCP result in lower SOC than SELF if the aging behavior differs. This grid area of KWH Netz GmbH, as given in Subchapter 4.3, reflects the load and generation profile data. Situated in upper Bavaria, Germany, a single selected 400 VAC LV grid, referred to as Moosham, provided the necessary input data for the simulation. With a relatively high share of RETs, mainly PV systems, the grid consists of three stub cable lines connected to a central transformer.

The grid contains 50 consumers and 18 PV systems with a total peak value of 307 kWp. The mean value of the installed PV systems is 17.1 kW, with a simultaneity factor of 0.85. The simultaneity factor considers that not all systems produce their maximum capacity the same time and may be influenced by cloud-drift and other factors, which resulted in a maximum power generation of 261.6 kW for the simulation. For the simulation of the different APM on the MP-BESS, both the accumulated load and generation profile of the grid area were taken. To emulate the load profile, 40 different statistically generated load profiles were generated, and each was scaled to the real annual electricity demand of every consumer in the grid [218]. The resulting annual minute-by-minute profiles were summarized to obtain an accumulated load profile, which is shown in Figure 57 left. The generation profile was simulated by scaling a representative PV profile from upper Bavaria to the overall installed PV power in the grid, multiplied by the simultaneity factor of 0.85, shown in Figure 58 right. The same generation profile, but scaled to the peak power of the PV systems, was used for all 18 PV systems.

Depending on the load profiles, the electro thermal model calculates the electrical behavior of the LIB cell, which includes the interdependencies between the voltage difference between the two cell terminals and the current flow as well as the resulting heat generation inside the cells. Therefore, at each simulation step, depending on the calculated stress factors, the capacity fade was simulated, and the BESS capacity was updated accordingly. The impedance and inner resistance parameters were updated for further aging estimations.

APM GRID, SELF, and SCP were given parameters based on [92, 117, 205, 219], and a pre-simulation was conducted. The resulting load profiles were evaluated with the aging model, and the parameters for updating the power flow model were calculated and looped back into the power flow model. The following discussion will briefly describe the resulting BESS behavior, estimate the capacity fade and interconnect the capacity fade with the model knowledge and LIB cell aging phenomena from the literature. Therefore, six different APMs, power profiles, were simulated according to previously explained APMs in Subchapter 5.2 and Chapter 3.

The APMs are GRID, SELF, SELF+GRID, SELF+GRID+SCP, PCP and SCP. The operation of the APM GRID limits the transformer power of the Moosham grid to a maximum of 157 kW, which corresponds to a 50% limitation of the installed PV peak power to comply with subsidy schemes in Germany. Transformer limitation is a bidirectional limit, inducing charge or discharge of the connected BESS, which is established to control the grid operation under the set limits.

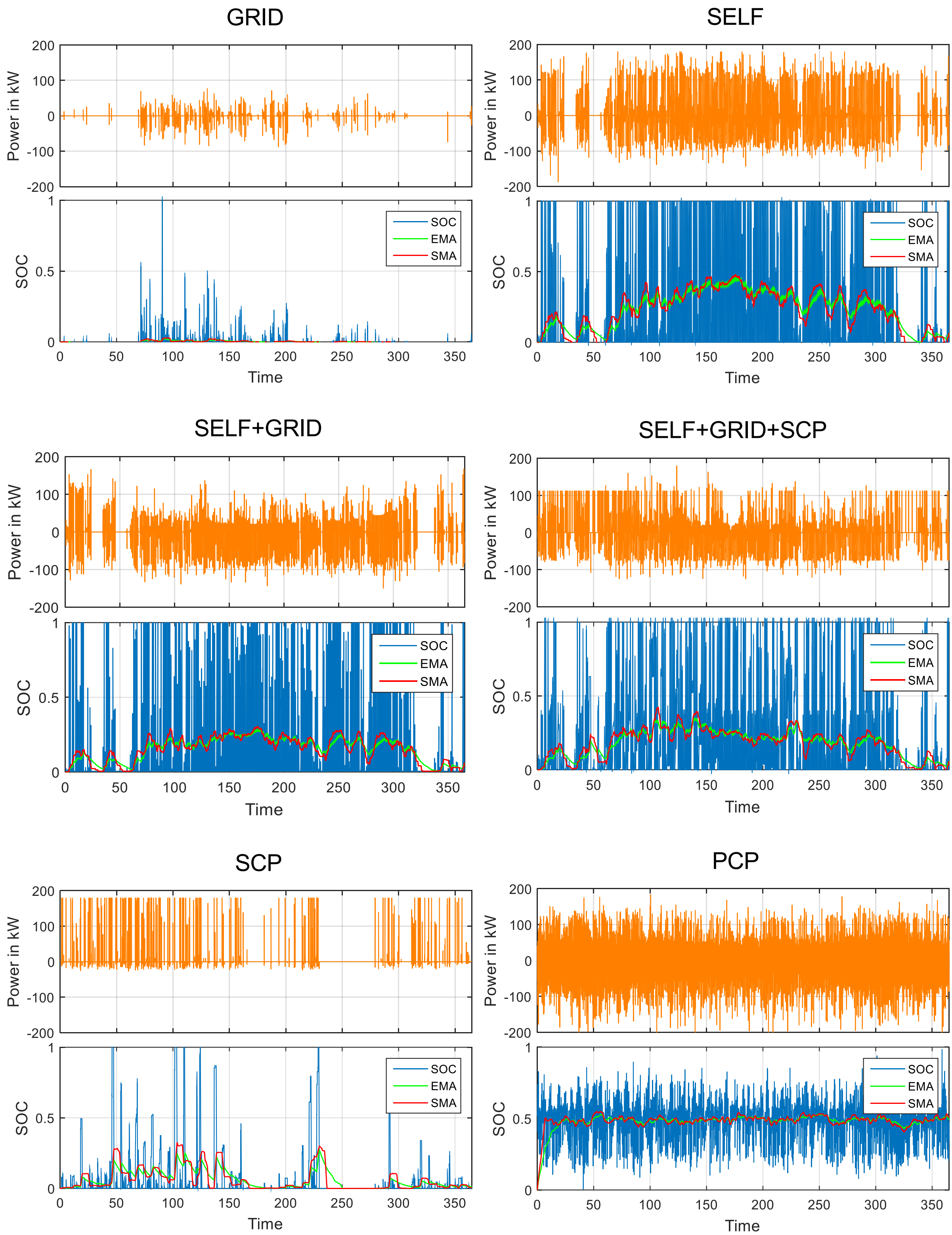

Figure 61 – Storage power flow profiles (orange) and SOCs (blue) for various APMs [206]. Data is given with the EMA (exponential moving average) and SMA (simple moving average) for better visualization.

The corresponding storage load profile is shown in Figure 61, top left; a positive value implies charging of the storage Operation of the BESS for APM SELF under a simple OS, referring to Subchapter 4.4, induces charging of energy whenever the grid load is smaller than the provided PV energy. In the case that grid demand and load exceed the available PV energy, BESS discharging is induced. Figure 61, top right, shows the corresponding load profile [220, 221]. Grid-friendly charging and discharging of the connected BESS APM GRID [117], similar to Subchapter 3.7, operates under the same control and strategy operations as SELF; however, charge and discharge currents are limited to a nearly constant value over the course of a day. The feed-in damping strategy ensures a fully charged BESS by the end of a day if the forecast is perfect. Figure 61, middle left, depicts the resulting load profile. The results indicate that because of the constant charging power limitation, the mean SOC is lower in comparison to the APM SELF; thus, a change in the aging phenomena is expected. The multiple use of BESSs, an MP-BESS, combines the APMs SELF + GRID and SCP. The provision for negative SCP in low tariff has been laid out to increase the utilization ratio of MP-BESSs [92]; however, its implications for BESS aging have not been addressed. Figure 61, middle right, depicts the corresponding power flow profile for the combined operation. SCP is provided with 125 kW in a virtual BESS pool, and the demand data were acquired by market research from [129]. The fifth APMs' SCP resulting power profile is depicted in Figure 61, bottom left. The provision of PCP, depicted in the bottom right, was outlined in detailed in Subchapter 3.7.

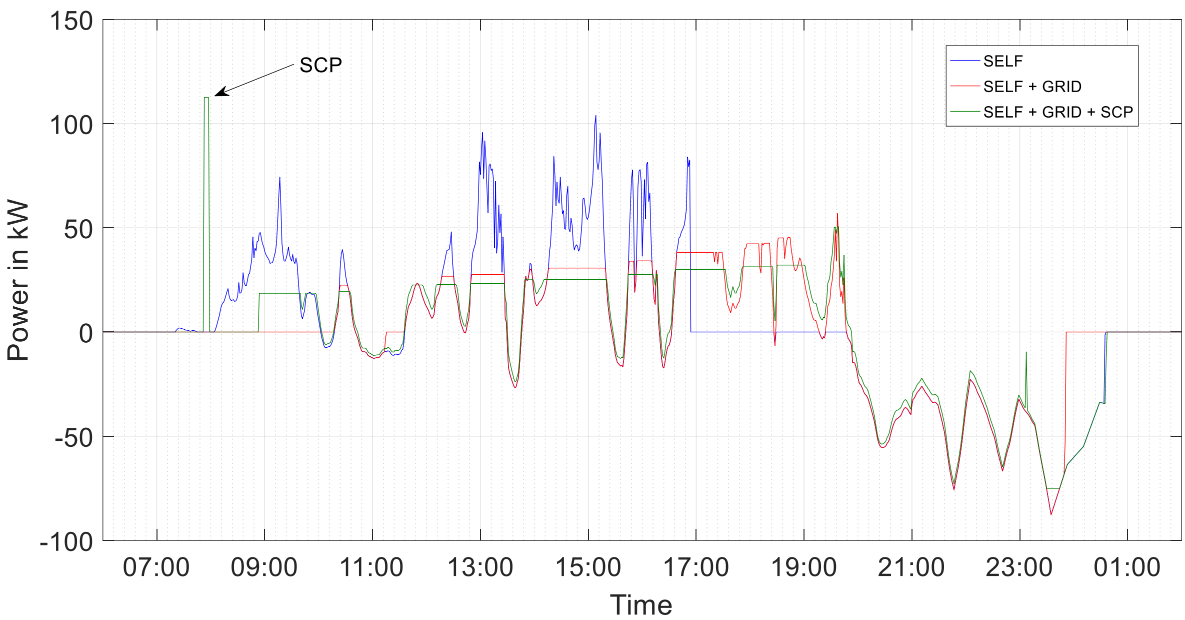

Figure 62 – Charge and discharge power in kW of a BESS running SELF, SELF+GRID, and SELF+GRID+SCP as APM for an exemplary day.

Figure 62 depicts an exemplary day running APM SELF, APM SELF+GRID and APM SELF+GRID+SCP for better understanding. The power shown represents the charge, if positive values, and discharge, if negative values, the behavior of the BESS. As explained in Subchapter 3.5 a simple OS for increasing SCR can be used, leading to the immediate charging of the BESS if PV surplus energy is available in the grid and immediate discharging of the BESS if the load exceeds the PV energy in the grid. Shown as the red line and further explained in Subchapters 3.3 and 3.5 a grid-friendly OS leads to a smarter charging strategy by cutting off all feed-in peaks into the grid by limited the maximum charge power by the estimated charge power, based on the PV energy, for the rest of the day. Further, the green line indicated the same BESS behavior which results by APM SELF+GRID, but additionally utilized some portion of the BESS for SCP participation. The data indicates, that early in the morning at 7:50 am an SCP market signal leads to a block charge of 115 kW for 15 minutes of the system providing negative SCP reserve power to the market. Consequently, the BESS SOC results high throughout the day and overall charging power, following SELF+GRID, decreases.

The following material briefly explains Figure 69 and the resulting aging speed based on the simulated APM and its resulting load profile and their respective capacity fade and attempts to explain an increase or decrease in aging. In addition, SOC and C-Rate histograms provide for better visualization.

The following graphs are normalized to a relative frequency of events according to the sum of 1-minute values for SOC and C-Rate over a one-year simulation. For better understanding, a color bar indicates, from purple (very low frequency) to yellow (very high frequency).

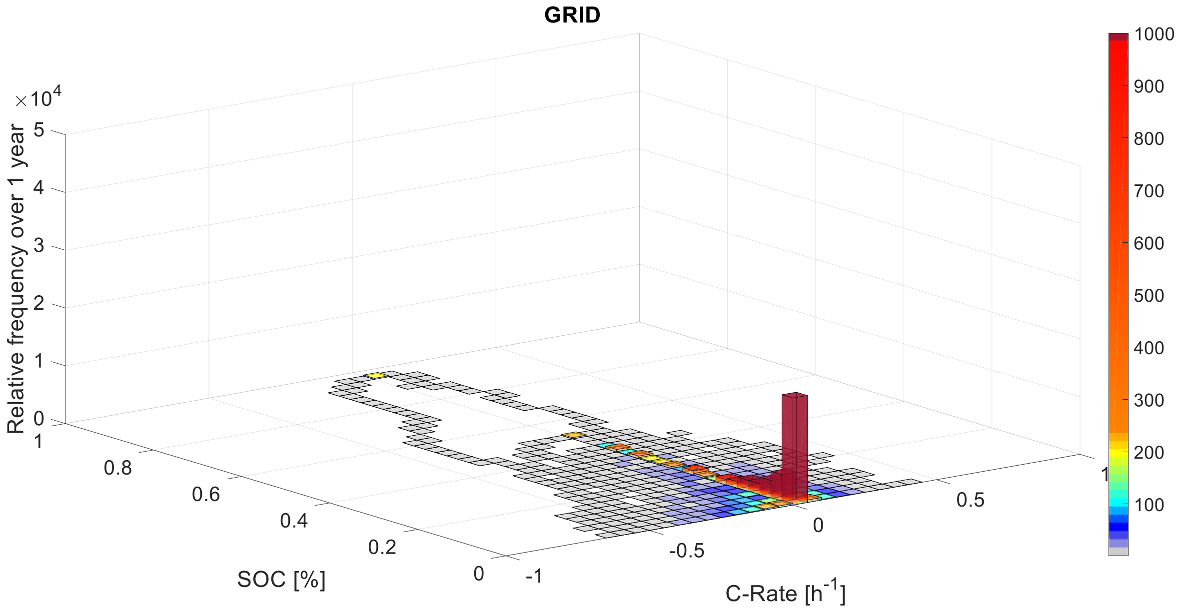

Figure 63 – Relative frequency of SOC and C-Rate for one year of simulation running APM GRID.

APM GRID (Figure 69, black curve) shows low activity rates (Figure 63) in terms of very low charging and discharging actions, low mean SOC values, lower power output and input (Figure 61), and low BESS utilization. Because of the low usage of BESSs, the aging behavior is primarily based on the BESS calendric aging. Results indicate that the BESS with APM GRID shows a loss in capacity of 2.9% after 3 years.

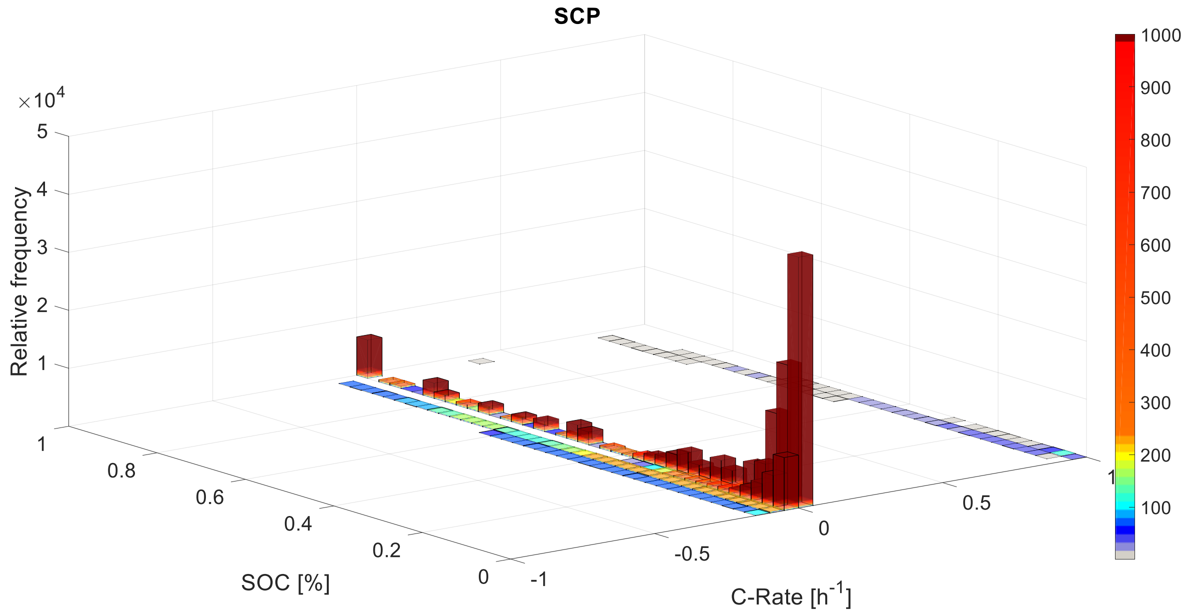

Figure 64 – Relative frequency of SOC and C-Rate for one year of simulation running APM SCP.

APM SCP (Figure 69, pink curve) shows a similar aging speed to that of GRID, reaching 96% rel. capacity after 3 years. While activity rates in the APM SCP seem to be higher, the activity time serving the SCP is limited. The average serving time with 125 kW lies between 15 to 19 minutes. Consequently, by taking the similar storage activity to GRID APM into account, the aging behavior is slightly increased. Figure 64 depicts that the storage, only providing negative SCP in LT, maintains very low SOC and C-Rates, though overall storage activity is slightly higher.

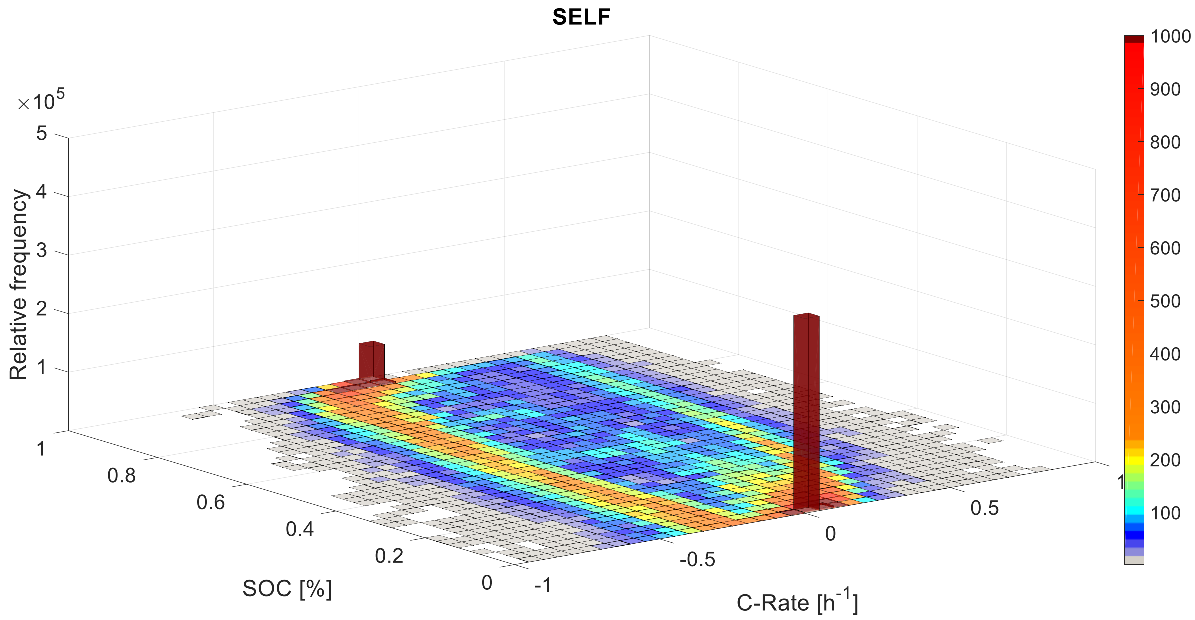

Figure 65 – Relative frequency of SOC and C-Rate for one year of simulation running APM SELF.

APM SELF (Figure 69, blue curve) shows the highest storage activity over one year, with the highest DOCs and longest charging and discharging times. As explained earlier, the greedy operation of a BESS charges any provided solar surplus energy into the storage and provides power as soon as required by consumers. This approach leads to large DOCs and high SOC states over many hours. The simulation results show a capacity loss of 21.5% after three years.

Results indicate that higher SOC states over a year and high DOCs with high C-Rates lead to faster degradation. Figure 65 underlines this observation indicating low SOC and C-Rates for the majority of BESS operation.

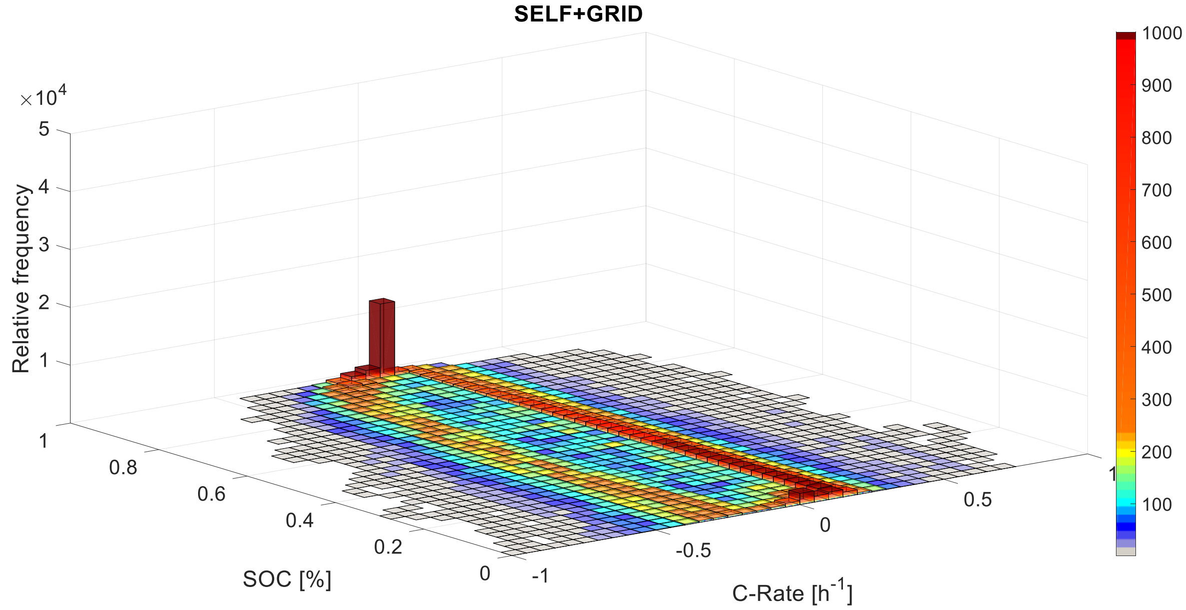

Figure 66 – Relative frequency of SOC and C-Rate for one year of simulation running APM SELF+GRID as an MP-BESS.

APM SELF+GRID (Figure 69, red curve) shows a decrease in the aging speed. After three years, a capacity loss of 17.8% is observed. While APM SELF represents the fastest aging speed of all the investigated APMs (Figure 69, red curve), the addition of APM GRID to APM SELF leads to a decrease in the aging behavior. While storage utilization and usage times do not interfere strongly, the change charging and discharging behavior lead to moderate SOCs (Figure 66). In addition to moderate SOC states, a decrease in the C-Rate can explain the reduced aging speed.

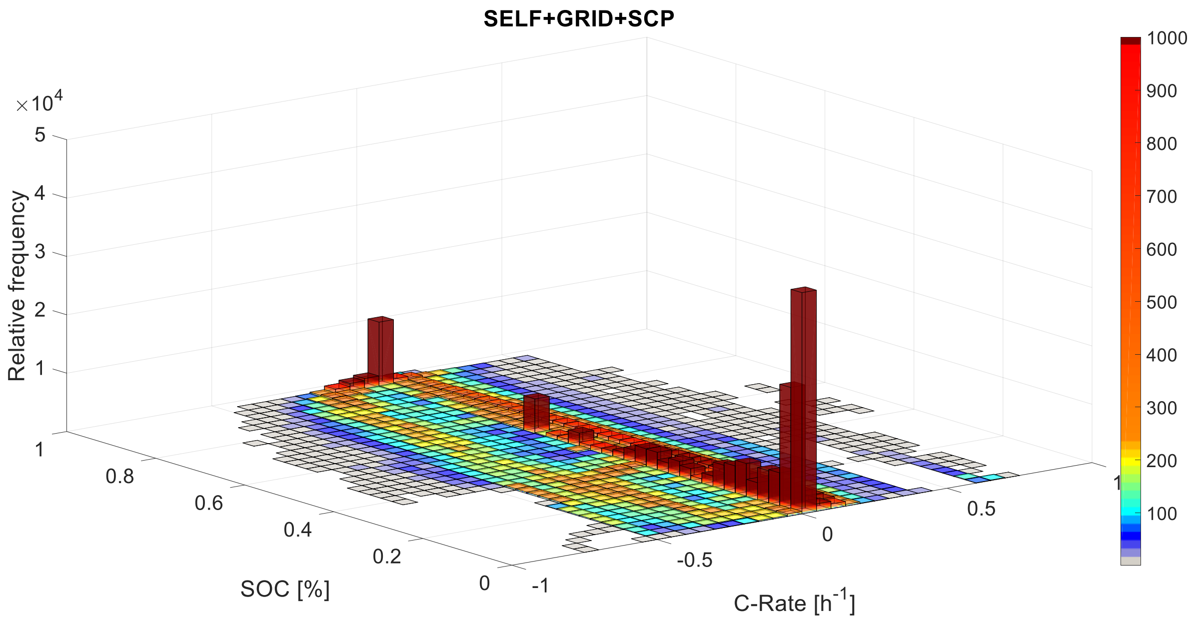

Figure 67 – Relative frequency of SOC and C-Rate for one year of simulation running APM SELF+GRID+SCP as an MP-BESS.

APM SELF+GRID+SCP (Figure 69, green curve) shows an additional decrease in the aging behavior relative to APM SELF and APM SELF+GRID with a capacity loss of 16.4% after three years. Overall, the storages' C-Rates and SOCs disposition are likely to be responsible for this behavior. The storage serves APM SCP up to 125 kW peak power at the same time APM SELF+GRID is active, which leads to a faster change in SOC_{mean} over a day and higher C-Rates for the whole system. These effects accumulate and produce a lower time of 100% and 0% SOCs because of the SCP charging, which positively affects aging.

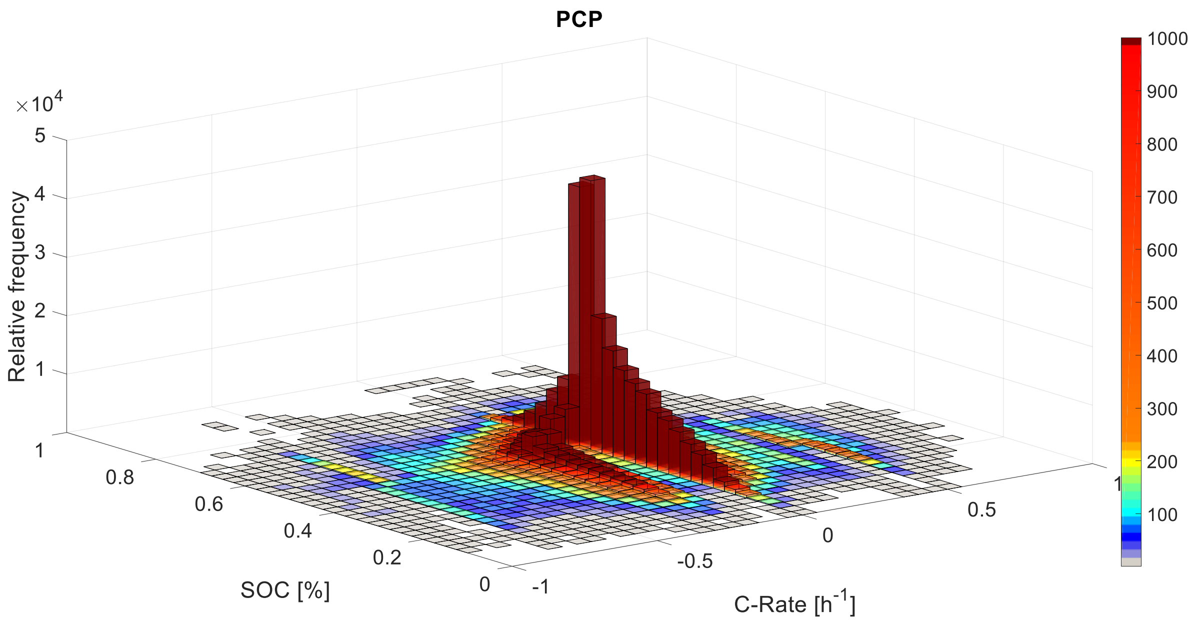

Figure 68 – Relative frequency of SOC and C-Rate for one year of simulation running APM PCP as an MP-BESS.

APM PCP (Figure 69, orange curve) shows a relative capacity loss of 7.5% after 3 years of extrapolated simulation data. By offering the PCP and following the P-f-characteristic balancing grid frequency, a much higher storage activity can be obtained. Nevertheless, C-Rates and the duration of cycles decrease significantly. In addition, PCP requires the BESS to stay at an average SOC of 50%. Data indicates that lower SOCs lead and a mean C-Rate of 0.5 to a decrease in the aging speed, whereas all other stress factors increase the aging behavior.

In summary, the combination of APM onto an MP-BESS shows a change in the aging behavior. The results indicate that this change is probably based on the differences in the mean SOC over a year of operation, changes in the average C-Rates and the resulting storage temperature. While PCP SOC remains at a mean value of $SOC_{mean} = 44.72\%$, APM SELF mostly represents one cycle with a DOD of 100% over each day of operation; thus, the SOC variance is larger than in PCP. In addition, less activity seems to lead to lower aging behavior, which is based on the shift from cycle aging to calendric aging.

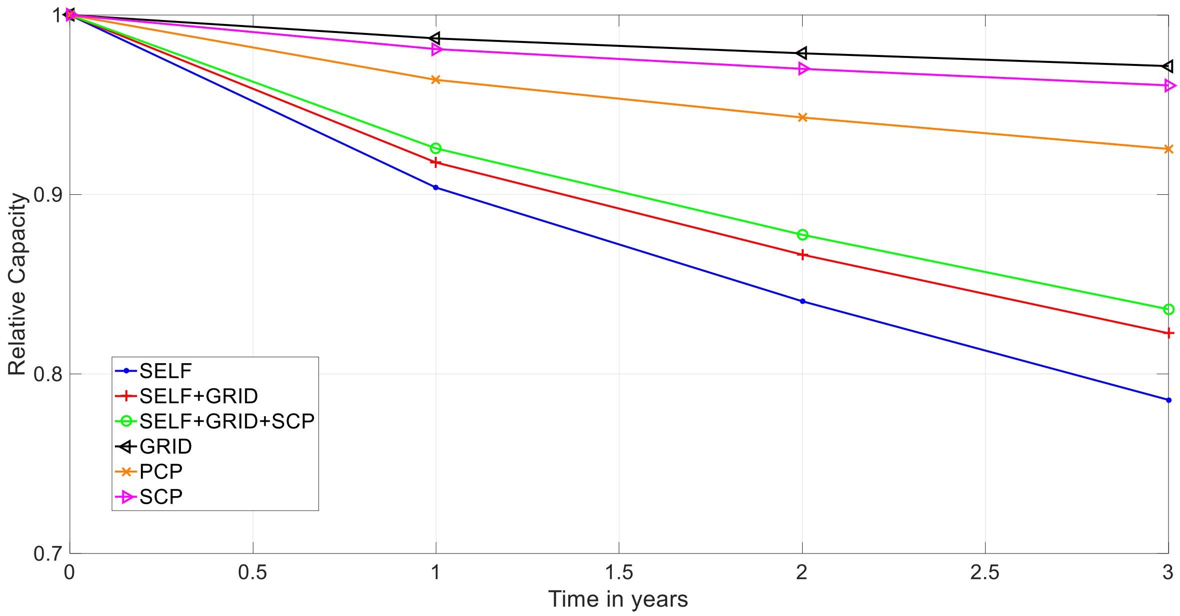

Figure 69 – Aging behavior of a simulated NMC technology-based BESS with six different APM [206].

In conclusion, APMs significantly influence the aging behavior of BESSs. Specifically, the combination of APMs can be used to manipulate the aging speed. A system state resting at 100% SOC shows faster degradation under the parameter set for NMC LIB relative to other SOC states. Thus, MP-BESSs should be operated in the direction of decreasing capacity fade by combining APMs onto BRs in a way to avoid critical, i.e., aging intensive, states.

5.5 Optimization Approaches for MP-BESSs

The following discussion will briefly introduce two optimization approaches for an MP-BESS. The general functionality of an MP-BESS was given in Subchapter 5.2, specifically that the division into BRs gives several benefits to the operator, as outlined in 5.1. The goal of the optimization of BESSs or MP-BESSs is to increase the overall ROI, i.e., the economic value of such systems. This can be achieved via a variety of approaches, e.g., increasing efficiencies or increasing tender bidding. For an MP-BESS with the proposed technical configuration, given in 5.1, optimization algorithms and techniques based on the possibility of dividing MP-BESSs into BRs are of special interest. Thus, the following material will show two ideas for i) optimizing the distribution of APM on an MP-BESS operating as CES and ii) optimizing the power distribution in such systems from the overall required system power flows on each BR. The effectiveness of such optimizations will be based on the reduction in the capacity loss.

5.5.1 Optimizing application mode and power flow allocation of single BR

BRs operating under different APMs and/or OS for an APM will encounter diverse power profiles over time because of the weekly SCP market tender biddings. Therefore, BRs operating in a specific APM is a degree of freedom in MP-BESSs architecture. The **random distribution** of APMs and an **aging-optimized distribution** of APMs onto several BRs was evaluated. The random distribution of APMs on BRs randomly distributes APMs on BRs via a simple randomizing function on a weekly basis. Figure 70 depicts the capacity loss occurring over a simulation time of one year under the constraints given in Subsection 5.2 for the exemplary case of low power and energy price bidding in the SCP market. This situation leads to high rates of participation in the SCP market, and aging phenomena are in a worst-case scenario. By randomizing APM distribution among available BR in an MP-BESS an equal distribution of aging behavior should be expected; however, the short simulation time of one year leads to differences in aging. In addition, even if randomized, a BR which already aged more will still get, even if randomized, the power demand an APM requires, leading to higher aging.

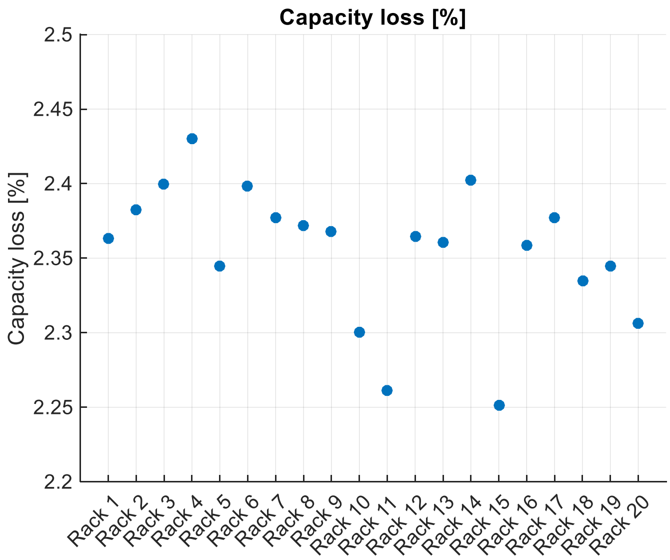

Figure 70 – Occurring aging per BR (n = 20) for randomized APM distribution over one year.

A very simple approach to reducing the aging in the MP-BESS is to distribute APMs for each period based on the correlating maximum capacity fade, i.e., the maximum available capacity from a BR's initial capacity. Sorting all available BR capacities, $C_{BR}(t)$, at the end of a period and accordingly distributing SCP on all BRs that show the least capacity fade and CSG on all BRs that show the most capacity fade will lead to a decrease in the overall aging among all BRs, see Figure 69. This assumption is drawn by the results shown in subchapter 5.4.

Following

$$C_{BR}(t) = \begin{pmatrix} C_{BR,1} \\ C_{BR,2} \\ \vdots \\ C_{BR,n} \end{pmatrix} \; with \; C_{BR,1} > \cdots > \; C_{BR,n}$$
$$\mathrm{APM}_{BR}\;(n) = \begin{cases} SCP \; if \; n \; \in [1, m] \\ CSG \; if \; n \; \in [m+1, n] \end{cases} \tag{62}$$

where $m \in \mathrm{SCP}_{BR}$ represents all available SCP BR from the pre-simulation, $n - m \in \mathrm{CSG}_{BR}$, and $n \in \mathrm{CES_{BR}}$. BRs with the least capacity face, i.e., the highest available capacity after consideration of the aging phenomena, are chosen first for SCP because the SCP load profiles are unknown for future weeks of operation. However, the results indicate that the contradictory strategy of

$$C_{BR}(t) = \begin{pmatrix} C_{BR,1} \\ C_{BR,2} \\ \vdots \\ C_{BR,n} \end{pmatrix} \; with\; C_{BR,1} < \cdots < C_{BR,n}$$
$$\mathrm{APM}_{BR}\,(n) = \begin{cases} SCP\; if\; n\; \in [1, m] \\ CSG\; if\; n\; \in [m+1, n] \end{cases} \tag{63}$$

may be beneficial in the case of realistic beddings for SCP market participation due to the fact, that SCP BR are assigned CSG BR in weeks where no tender can be obtained.

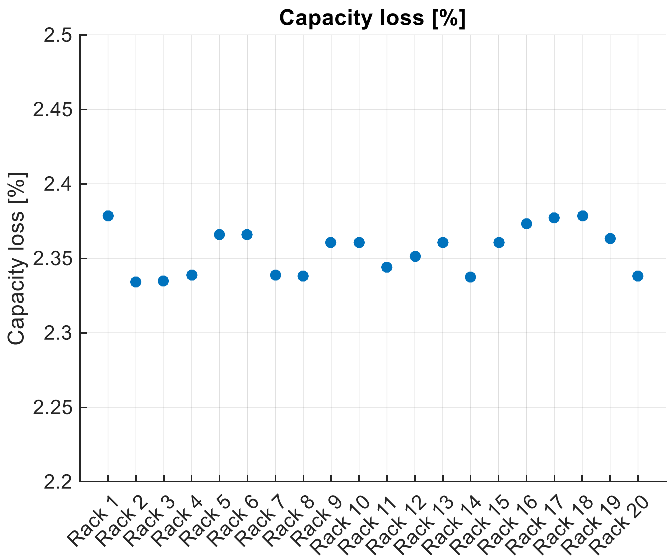

Figure 71 – Aging per BR (n = 20) for aging optimized APM distribution over one year.

Figure 71 shows the resulting capacity fade for n = 20 BR over a simulation period of one year by applying the aforementioned logic of equation (62) for APM distribution on the MP-BESS. The overall aging, as a mean capacity fade over all 20 BR, remains almost the same; however, the aging distribution is more uniform. This effect can be beneficial for storage operators and financial stakeholders by giving a better estimate of the total lifetime for such systems ultimately lowering replacement cost due to a uniform aged system.

In addition to the distribution of APMs, the power, P_{stor}, can be distributed among all BRs according to each BR's individual APM over time. First, a similar case to a randomized APM distribution is transferred to power an equal distribution of power. Via the ratios between the required power per APM and BR, $P_{Rack\ CSG}$, and the overall existing BR power for an APM, $P_{Rack\ CSG}$, the share as an absolute number per time step, t, can be estimated, see equations (57).

An aging optimized solution for the distribution of power to BRs is achieved by calculating the necessary energies for CSG- and SCP operation:

$$E_{CSG}(t) = P_{StorCSG}(t) * \Delta t$$
$$E_{SCR}(t) = P_{StorSCP}(t) * \Delta t \tag{64}$$

and an estimation of the possible charge C_{char} and discharge C_{dis} capacities per BR for each time step, t, of the simulation are calculated as follows:

$$E_{char}(n) = 1 - \left(SOC_{Rack}(t) * E_{Rack}(t)\right) \forall\, n\; Racks$$
$$E_{dis}(n) = \left(SOC_{Rack}(t) * E_{Rack}(t)\right) \forall\, n\; Racks \tag{65}$$

$$\underline{E}_{CSG_{BR} \setminus SCP_{BR}} = \begin{pmatrix} E_{dis}(1) \\ \vdots \\ E_{dis}(n) \end{pmatrix} \; with\; E_{dis}(1) > E_{dis}(n) \tag{66}$$

$$\underline{E}_{CSG_{BR} \setminus SCP_{BR}} = \begin{pmatrix} E_{char}(1) \\ \vdots \\ E_{char}(n) \end{pmatrix} \; with\; E_{char}(1) > E_{char}(n) \tag{67}$$

by sorting the CSG BR and SCP BR according to their available charge or discharge capacity. The total number of BRs necessary for the power requirements and the ratio of BR power to total storage power are calculated; while $|E_{CSG}(t)| > 0 \vee |E_{SCR}(t)| > 0$ is true, for all $n = BR_{SCR}$, follows

$$E_{CSG} = E_{CSG} - E_{char}(n)\; for\; E_{CSG} \geq 0$$
$$E_{CSG} = |E_{CSG}| - E_{dis}(n)\; for\; E_{CSG} < 0 \tag{68}$$

$$BR_{Share\;CSG}(n,t) = \begin{cases} \dfrac{E_{char}(n)}{E_{CSG}(t)} \;\forall\, E_{CSG} \leq 0 \\ \dfrac{E_{dis}(n)}{|E_{CSG}(t)|} \;\forall\, E_{CSG} > 0 \end{cases} \tag{69}$$

and for $n = BR_{CSG}$,

$$E_{SCP} = E_{SCP} - E_{char}(n)\; for\; E_{SCP} \geq 0$$
$$E_{SCP} = |E_{SCP}| - E_{dis}(n)\; for\; E_{SCP} < 0 \tag{70}$$

$$\mathrm{BR}_{\mathrm{share}_{SCP}}(n,t) = \begin{cases} \dfrac{E_{char}(n)}{E_{SCP}(t)} \;\forall\, E_{CSG} \leq 0 \\ \dfrac{E_{dis}(n)}{|E_{SCP}(t)|} \;\forall\, E_{CSG} > 0 \end{cases} \tag{71}$$

For the total power requirements per BR, let n be the total number of CSG BR and n be the total number of SCP BR:

$$P_{CSG,\mathrm{n}}(t) = BR_{Share_{CSG}}(n,t) * P_{Stor_{CSG}}(t)$$
$$P_{SCR,n}(t) = BR_{Share_{SCP}}(n,t) * P_{Stor_{SCP}}(t) \tag{72}$$

Figure 72 depicts the decreased spread in capacity fade over a simulation run for one year when simultaneously optimizing APM distribution for CSG and SCP on CES operating MP-BESSs and optimizing the power distribution on all available BRs per APM on a weekly basis.

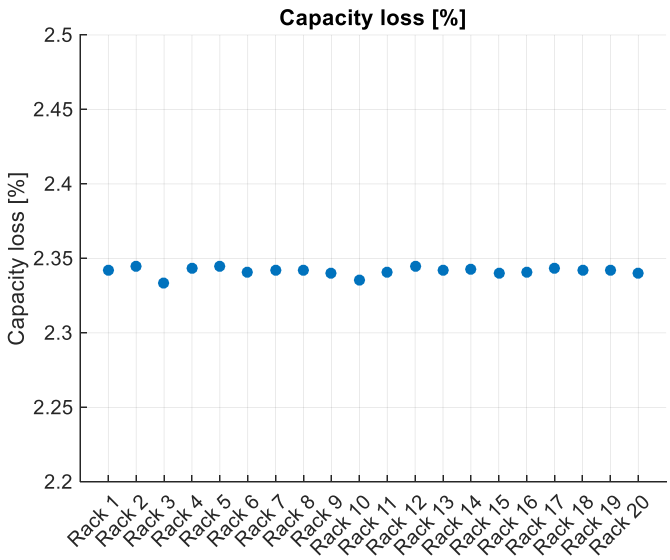

Figure 72 – Aging occurring per BR (n = 20) for aging optimized APM distribution over one year.

Algorithms can greatly manipulate internal MP-BESS states and influence parameters such as capacity fade or efficiency of the system. The need for sophisticated EMS is apparent. Apart from APM distribution, the division into BRs with independent PE is advantageous because of the additional degrees of freedom. For PE simulations the PE efficiency depends on the power output and is implemented via

$$\eta_{PE} = f\left(p = \frac{p_{out}}{p_{rated,PE}}\right) = \frac{p}{kp^2 + p + p_0} \tag{73}$$

with the following parameters

$$\mathrm{k} = 0.0345; \mathrm{p}_0 = 0.0072 \tag{74}$$

analog to [158] based on [222]. Therefore, the operation of an MP-BESS divided into a number of BRs can provide the benefits of separation into smaller BRs with independent BRs. Figure 73 depicts the possible efficiency benefits from switching BRs and PE. The left figure shows an MP-BESS with a linear load increase when the system is divided into different sized PE and BRs, which both differ in peak power (kW) and energy content (kWh). There, with a randomized selection after each BR is at its full peak power, the next BR is added to the cluster of BRs to serve the overall MP-BESS power requirement.

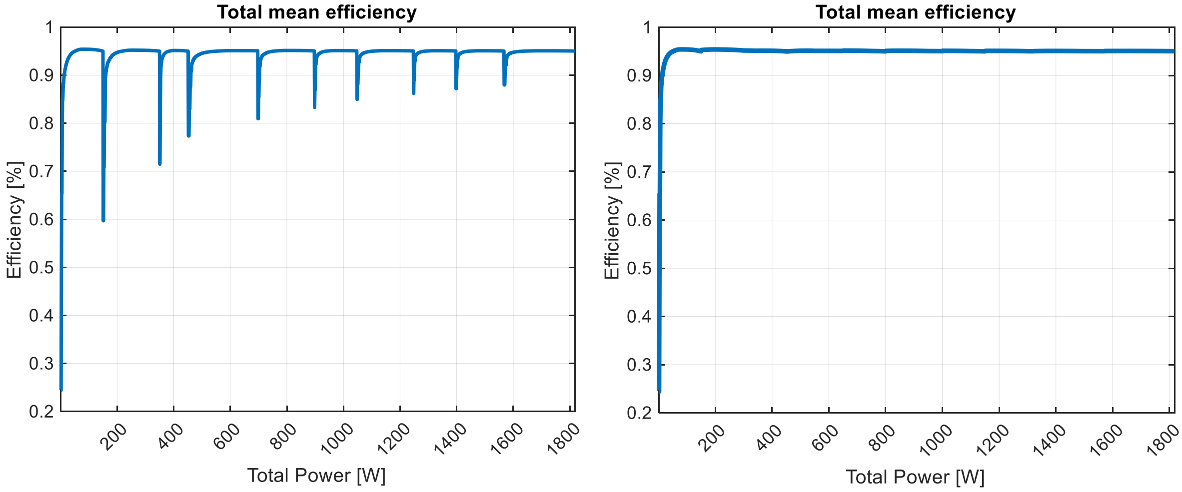

Figure 73 – Efficiency optimization of an MP-BESS for intelligent switching of PE and BRs (right) compared to simple switching of PE and BR units.

The right figure shows the optimized operation of BRs and their individual PE units. Common PE units show an efficiency of over 90% at 10% maximum power output, which is used in this approach. Whenever the maximum peak of a PE unit is reached, the next unit will not be added after the initial one peaks at its power limit, but it will be activated simultaneously and instantly with at least 20% of its maximum peak power. The resulting total mean efficiency of the system can be increased significantly.

5.6 Economics of MP-BESSs

The following material will give a brief introduction to the calculations regarding the economics of MP-BESSs. However, these vary vastly for different value estimation approaches, legal frameworks, and other boundaries and serve only as an indicator of a beneficial outcome from subdividing MP-BESSs into a number of BRs. Therefore, revenue calculations for participation in the SCP market, IDM, and CSG will be given separately. First, the SCP revenue calculations were performed by adding the achieved power price revenue and the energy price revenue at the specific tender bids. If $Inc_P(w)$ is the total income per week, $p_{power}(w)$ is the offered power price in the tender and $P_{SCPOffered}(w)$ is the offered SCP power per week, then the total income from SCP over a year is as follows:

$$Inc_P(w) = p_{power}(w) * P_{SCP_{off}}(w)$$
$$Inc_{P,total} = \sum_{w=1}^{52} p_{power}(w) * P_{SCP_{off}}(w) \tag{75}$$

The similar energy income is given by

$$Inc_E(w) = p_{Energy}(w) * E_{SCPStorage}(w)$$
$$Inc_{E,total} = \sum_{w=1}^{52} p_{Energy}(w) * E_{SCPStorage}(w) \tag{76}$$

The income from IDM trading is given by

$$Inc_{IDM}(t) = \int p_{IDM}(t) * P_{IDM_{off}}(t)\, dt \tag{77}$$

which sums the overall SCP market revenue for the simulation period. Figure 74 depicts the absolute revenue for four different scenarios, which serve as examples to better understand the dynamics of MP-BESS division into BRs. An MP-BESS with 20 BRs achieves a higher revenue during the same period in the same market relative to an MP-BESS of the same power and storage energy with 4 BRs. Another dimension is given by showing the differences between OS "greedy" and "feed-in damping" for such systems, where feed-in damping achieves higher revenues with the same BR number. First, additional BRs lead to higher revenues at a similar CAPEX for the overall MP-BESS because of the flexibility for assignable battery capacity on each APM. Thus, a system with an infinite number of BRs will have the maximum possible revenue, but this scenario is not feasible.

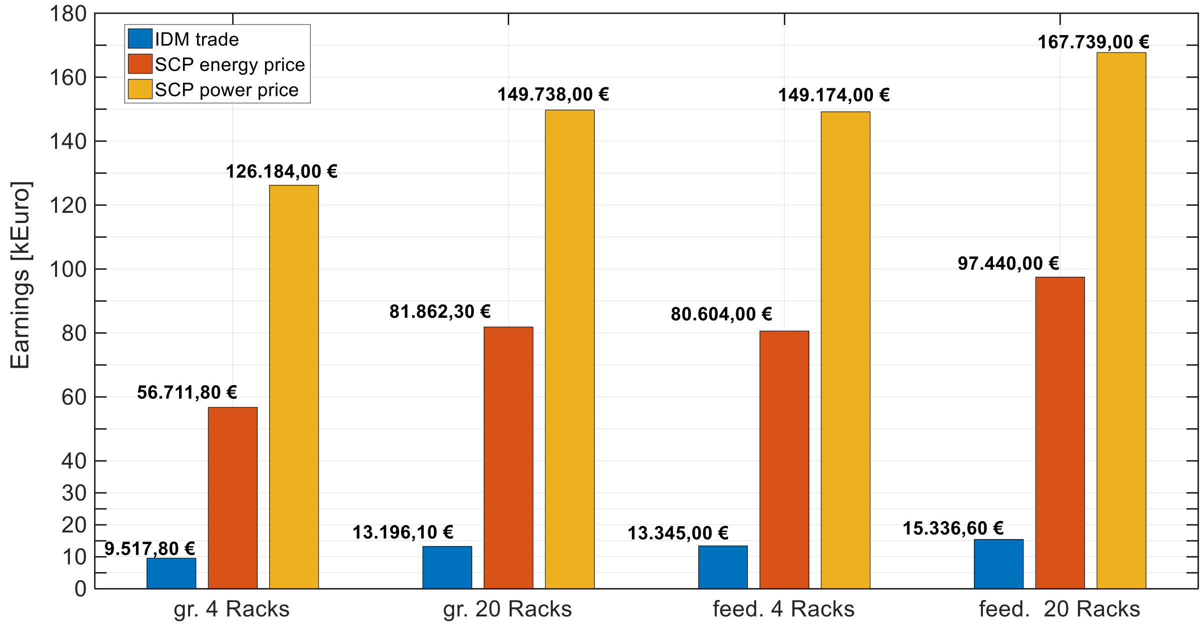

Figure 74 – Total possible revenues for three years from the IDM market and SCP market for 4 and 20 BRs operated with OS greedy or feed-in damping for three-year simulation (2013, 2014, 2015). A total storage size of 5,5 MWh and power 5,5 MW remains unchanged during simulation.

Additionally, the OS has a strong influence on MP-BESS behavior. While 20 BRs with a greedy OS gain a revenue of 149.738,00 €, an MP-BESS with only four BRs operating a feed-in damping OS gains a revenue of 149.174,00 €. The dimension for finding an optimal OS for BESS optimization was not investigated in depth in this work. However, literature research led to the decision to operate all CSG BRs with OS feed-in damping based on [117]. Higher revenues due to a change in OS for CSG occur by the OS's positive influence on weekly maximum SCP bids. In other word, if the CSG operation is optimized with an OS, i.e. feed-in instead of greedy, the MP-BESS can utilize more BR for SCP, thus generate more revenue upon this market.

The economics of CSG operation are based on the assumption that any electricity that can be charged in the MP-BESS and provided in times of low or no solar irradiation to the grid connected loads, e.g., households, will save grid consumption and reduce the actual electricity cost ($€/kWh$). The power to and from the grid, $P_{grid}(t)$, in each time step, t, leads to cost savings.

$$P_{grid}(t) = P_{StorageCSG}(t) - P_{PV}(t) + P_{Load}(\mathrm{t}) \tag{78}$$

Therefore, all energy that was bought or sold from or to the grid must be accounted for:

$$\begin{aligned} Ele_{purch} &= \int P_{char_{grid}}(t)\, dt \\ Ele_{Sold} &= \int P_{dis_{grid}}(t)\, dt \end{aligned} \tag{79}$$

In addition to the revenue via grid feed,

$$Inc_{Remun}(t) = Ele_{Sold}(t) * p_{Remun}(t) \tag{80}$$

The cost of energy from the grid is

$$Cost_{Energy}(t) = Ele_{Purchased}(t) * p_{Energy}(t) \tag{81}$$

Resulting in the following cash flow from CSG operation:

$$Ca_{Flow}(t) = Cost_{Energy}(t) - I_{Remun}(t) \tag{82}$$

In addition to the energy and energy cost approach, capacity fading related cost of storage is as follows:

$$Cost_{Aging} = \Delta C_{Calyear} * p_{calyear} + \Delta C_{Cycyear} * p_{Cycyear} \tag{83}$$

where $p_{calyear}$ is the cost per kWh estimated by the calendric aging and $p_{Cycyear}$ is the cost per kWh for cyclic aging, and the loss of capacity by $\Delta\mathrm{C}$ is given. However, feed-in revenues only occur under fitting legislative framework and may not be subject for a large MP-BESS.

Figure 75 depicts the overall economics for an MP-BESS operating CES for three years. The boundary conditions were the number of BRs, i.e., 4 and 20, and an OS of either "greedy" or "feed-in damping." For an MP-BESS with 5.5 MW and 5.5 MWh operating three years the total profits vary from 128.617 € up to 585.946 € over the range of three years. The range of results and economic figures are problematic for modeling BESSs. The large number of input variables, i.e., the load profile or the generation profile of the underlying grid, the price per kWh or per kW, aging modelling and parameters, and other boundaries during the simulation, i.e., power electronics efficiencies, and battery efficiencies, lead to results that can vary dramatically by changing only one input parameter. The differences become apparent when comparing the price scenarios. The minimal price scenario is a price of 625 €/kWh, and the maximum price scenario is a price of 960 €/kWh. However, a clear trend can be observed, namely that the worldwide batteries and BESS prices are decreasing dramatically [44], which will ultimately lead to higher economic values, and over a 20 to 30 year lifetime of MP-BESSs there will be the potential for economic utilization.

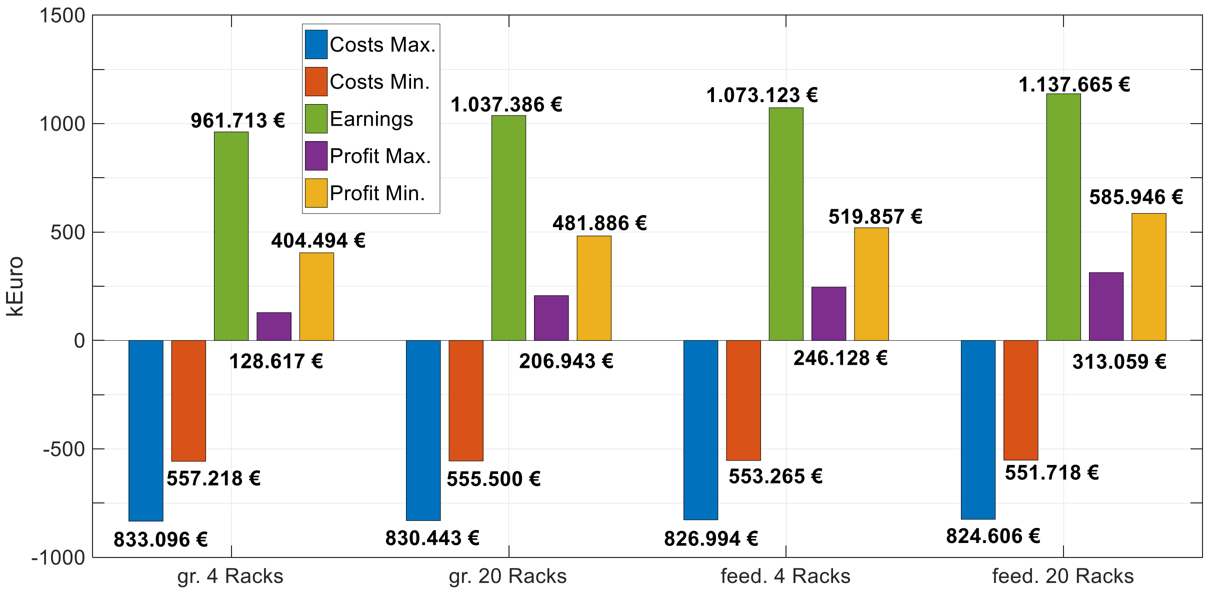

Figure 75 – Cumulated economics from the IDM market and SCP market for 4 and 20 BRs operated with OS greedy or feed-in damping for three-year simulation (2013, 2014, 2015). A total storage size of 5.5 MWh and power 5.5 MW remains unchanged during simulation, under the constraints of minimal and maximal pricing scenarios [223].

5.7 Conclusion

Within the scope of this chapter, a comprehensive view of using a BESS as an MPT was outlined by providing the basic concept for MP-BESSs and examining it accordingly. Additionally, the fundamental use of BESSs as an MP-BESS was described. The results indicated that the proposed MP-BESS topology is only one of several approaches to ultimately increase the economic value of BESSs by overcoming technological or legal hurdles. An exemplary implementation of an MP-BESS was given, and its results were published in [92]. The results indicate that the utilization ratio of a BESS is a sound indicator for estimating the overall economic value. Data indicated that several APMs show a very low utilization ratio over an operating period, which ultimately leads to an unnecessary loss in economic value.

In addition to the fundamental experiments and simulations, a relatively complex simulation analyzed the influence of operating a BESS as an MP-BESS, i.e., stacking several applications on one system. This simulation was performed to prove that stacking several applications will induce a higher utilization of BESSs, which will finally result in a decrease in economic value. The resulting data indicated that the multiple use of a BESS, i.e., an MP-BESS, will lead to a decrease, but not in all circumstances in capacity fading mechanisms. By stacking several APMs on a single BESS, the technical parameters over the simulation time of three years, i.e., the mean SOC values, mean DOC values and others, changed in a way that resulted in less capacity fading. Furthermore, the positive effects of application stacking depend on the APMs' power profile; however, all the results were obtained for a single LIB cell chemistry under one specific configuration of BESS parameters and must be counter proven using a wide-ranged sensitivity analysis. Figure 76 depicts the increase in BESS utilization by showing every hour per day for a full year in respect to absolute BESS power. IDM and SCP stacking leads to higher use of the storage, and the overall storage power is used as well. A comprehensive simulation approach for the previously defined system topology was provided regarding the operation and simulation of an MP-BESS. This simulation was performed to provide technical proof for the overall idea of APM stacking, which is spreading in industry.

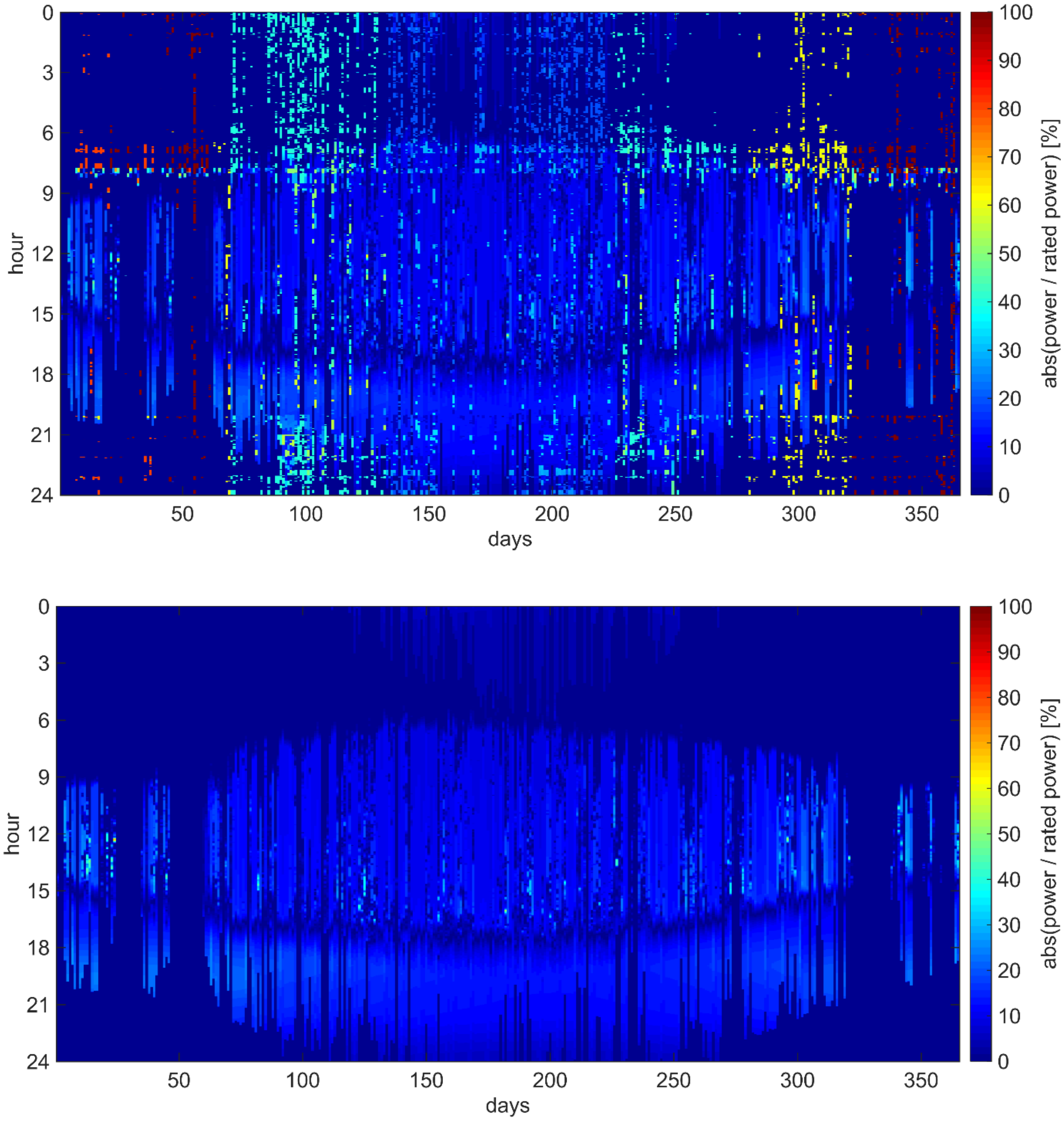

Figure 76 – Heatmap showing the power of an MP-BESS operating CES (top) and an MP-BESS operating CSG only (bottom).

Focusing on power flow models and overall simulation functionality rather than providing an in-depth simulation toolbox enhances overall understanding. Regarding the implementation of two optimization approaches and system topology, the findings and method for MP-BESS are promising, as the adoption of economic analyses clearly showed the benefit of the MP-BESS approach. However, a major issue is the reliable fit of the technical parameters for the system, which cannot be wrong under any circumstances. Thus, it is relevant to find the ideal set of parameters for the BESS simulation environment and outline extensive sensitivity analyses.

Furthermore, regarding the effect of total system cost, low values are regarded as too optimistic for economic valuation. (The overall system ROI is largely dependent on CAPEX cost.) Finally, if the special characteristics of MP-BESS are considered with regard to an adequate parameter and input profiles, MP-BESSs might be economically beneficial over existing BESS architectures and approaches for the current operation of BESSs because of the increase in economic value.

6 Multipurpose BESSs: Legal Aspects and Business Models

To achieve an energy transition in Germany, BESSs must be part of the transition approach. There is a broad range of possible applications for BESS because of the technical conditions, as opposed to the economic or legal conditions, are favorable. Under current legal and regulatory conditions in Germany, the exclusive use of a single APM for BESSs is rarely profitable. The following chapter will propose three different business models and an approach to implementing MP-BESSs under the current legal framework in Germany.

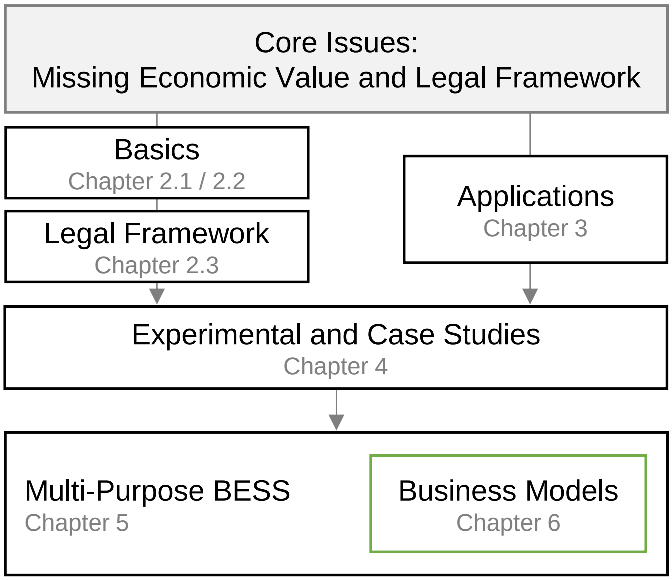

Figure 77 – Work progress in Chapter 6.

A combination of storing PV surplus energy, relieving grid overloads, providing control reserve and interaction in an energy exchange in one single BESS is economically meaningful, as presented in Subchapter 5.6. Thus, MP-BESSs in LV distribution grids can achieve economic profitability, as presented in Subchapter 5.6. Subchapter 6.1 presents an original view on new proposed business models within the legal boundaries in Germany for MP-BESSs.

Matching the previously stated APMs consecutively results in three theoretical business models: community battery storage, leasing, and electricity tariff models (ETMs). Each of these models has different benefits for the respective stakeholders. Therefore, there is no clear preference regarding marketability drives. Despite a thorough examination of the regulatory status quo in Germany, it cannot be confirmed with certainty whether these operational concepts can withstand a practical test, mostly in terms of economic benefits. In consideration of the German energy market rules, laws, regulations and directives, several business actors and compatible APMs for MP-BESSs emerge, which the following subchapter will show. In addition to legal and regulatory framework conditions, economic framework conditions also have a significant impact on the success of new technologies, i.e., the MP-BESS. The contemplated investment costs and various other parameters have an economic impact on the business models. These include electricity costs and renewable energy feed-in remuneration. However, this work does not include a concrete economy calculation for all three models, and the investigations do not cover the framework conditions. Full economic calculations for the described models would only be relevant for a short time because regulation and governmental directives change quickly.

Furthermore, because of the dependence of a large number of parameters and their individual range, even the results of a broad sensitivity analysis on economic performance may not be usable because of significant uncertainties. Thus, this work proposes fundamental thoughts on BESSs, specifically MP-BESSs, and business models functioning under current (as of 08/2016) conditions, but is not bound to these.

6.1 Business Models

Matching the interests of the different stakeholders and the APMs successfully results in three theoretical business models. A grid-optimized operational strategy for MP-BESSs concerning the feed-in power of PV systems, as shown in [117], including arbitrage at the continuous intraday market and providing negative low tariff SCR, seems to be the most reasonable approach under current (as of 09/2016) regulatory influences on the business models (See Subchapter 5.2.). Because of the peculiarity of the MP-BESS, especially the flexible combination of PE and BR, all APMs vary in the share of the MP-BESS throughout the year and throughout the day. Thus, differences occur depending on the intensity of insolation and possible revenues in the other three markets.

Financing and an appropriate legal form are essential for ownership and operation of the BESS. Various options for financing, such as leasing and contracting, exist if the equity is insufficient. For the considered storage size, an energy cooperative with a higher investment, a “GmbH & Co. KG,” appears to be an adequate legal form, if an existing company does not invest and take over operation of the BESS. The latter is a special German mixed legal form, where a limited company, acting as a general partner, substitutes the natural person of a limited partnership. Therefore, the “GmbH & Co. KG” combines the advantages of a corporation with those of private companies, and the contractual arrangement can be strongly influenced by all parties. In contrast, cooperatives have little flexibility because of the strong legislative influences. The reasons for establishing energy cooperatives include promoting a sense of community, making a profit, and ensuring the regional energy supply and independence from energy companies, according to a survey by the Klaus Novy Institute [224–228].

In the following discussion, three approaches for business models for MP-BESSs in LV grids are discussed; these approaches consider the technical peculiarities of the system and the selected, compatible APMs.

6.1.1 Community Battery Storage

The first business model described focuses on public or citizen solar parks and is entitled “*community battery storage*.” Solar system operators and any electricity end users join an energy cooperative. In this case, the MP-BESS is owned by this cooperative, and each member receives a share based on his or her capital contribution. Usually, the necessary professional competence and expertise are lacking, and the MP-BESS is operated by an ESC. The ESC can hold a share of the cooperative. Because the MP-BESS is owned by the cooperative, its members either use a specific part of the system or lease to the operating ESC.

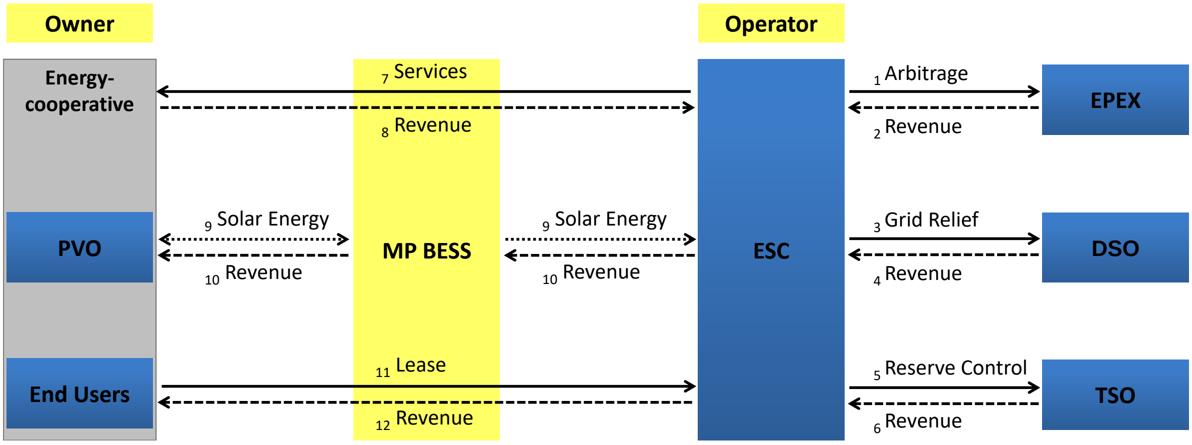

Figure 78 – Community battery storage: Flows of cash, goods and services.

Figure 78 shows the flows of cash (dashed line), goods (dotted line) and services (solid line) in this model. An ESC generates revenues for the cooperative (2, 4, and 6) via interactions in the energy exchange (Arbitrage) (1), relieving grid overloads (3) and providing negative low tariff SCP (5). The cooperative remunerates (8) these three services, including the operation (7). The revenues from the three services are passed on to the cooperative, which leads to an ROI for its members. The possibility of profit sharing exists as an incentive for the cooperative to achieve an increased overall efficiency. The ESC keeps a part of the earned revenues because it provides the services. Furthermore, PV system operators (PVOs) use the MP-BESS for temporary storage of PV surplus energy per their share. While the solar power (9) is primarily used for the cooperative's own consumption, the excess is sold. The ESC remunerates (10) the final surplus and uses it depending on their portfolio. Any member of the cooperative can lease an individual share or a part of it (especially during low insolation, e.g., in the winter) to the ESC (11) to gain revenue (12). The latter is the only possibility for end users without a PV system to achieve additional benefits from the cooperative in addition to the cash flow from the services provided by the ESC. Therefore, the ROI is much higher when a member of the cooperative is also a PVO because of the cost savings from an increasing SCP.

6.1.2 Lease Model

The second business model is termed the "*lease model*," and leaseholders have the right to use the leased capacity and power. Thus, the contract addresses not just assets but also their use. A lease model is a form of financing similar to operate-leasing (e.g., renting an apartment) and finance-leasing (e.g., leasing a car). Further information is provided in [226, 229] and the German Civil Code ("Bürgerliches Gesetzbuch"), especially §§ 535 – 546, 581- 597 and 835 et seq.

The flows of cash, goods, and services in the lease model are depicted in Figure 79, in which the type of line corresponds to the previous model. With this business model, one ESC combines the property and operation of the MP-BESS, and their services obey the model above (1, 3, and 5), except that the cash flows are not redirected to a cooperative and stay in the ESC (2, 4, and 6).

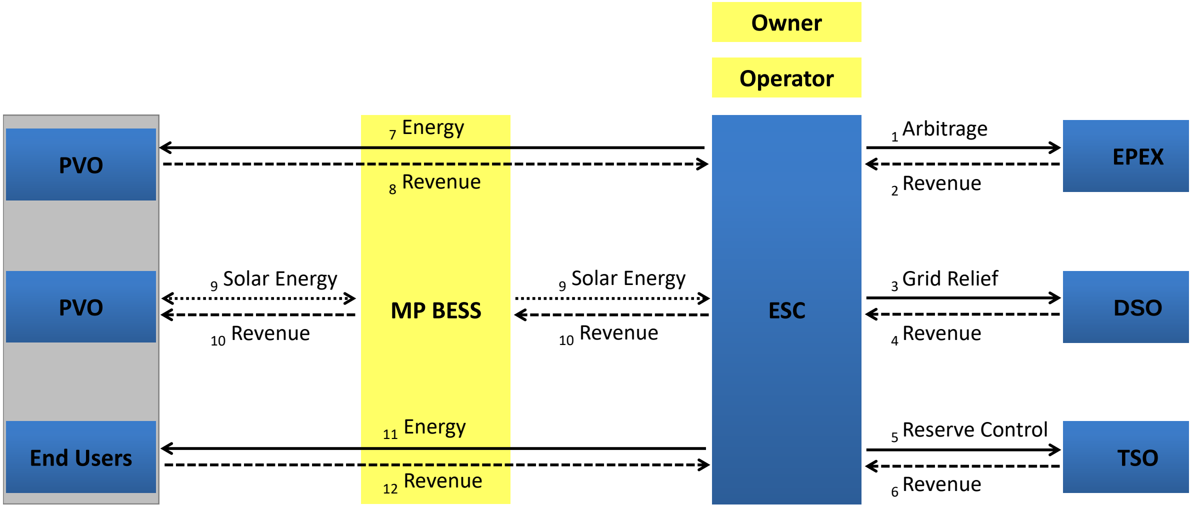

Figure 79 - Lease model: Flows of cash, goods and services.

Because of the use of a specific part of the MP-BESS by PVOs, ESCs will also receive the lease amount (8 and 12). Furthermore, power customers without a PV system receive no benefit from this model. The success of this model depends on the lease amount. A lease can be purchased for an entire year (7) or for less than a year (11). During periods of high insolation, PVOs prefer a higher storage capacity. The ESC generates additional revenues with a higher rate of operating activities, and the lease is a secure source of income.

The PVOs use their shares of the MP-BESS for temporarily storing PV surplus energy. Again, the solar power (9) is primarily for PVO consumption, but it is also for sale, and the ESC remunerates (10) the final surplus.

With this business model, the design of the lease contract is the main concern. According to [69], the lease alone does not show a positive ROI for the ESC. To ensure a benefit from providing the three mentioned services, the ESC needs to determine the availability of the capacity and power to the PVOs. Considering weather forecasts and load curves, the ESC needs to use the highest possible share of the BESS. Therefore, the contract must include a clause where a certainly available proportion of the BESS is guaranteed to the PVOs, which results in a reduced investment risk for both parties

6.1.3 Electricity Tariff Model

The third business model is termed the "*electricity tariff model*" and presents the merger of possession, property, and operation by the ESC. Since the ESC takes on finance, procurement, and installation of the MP-BESS as well as the power supply, this model is legally classified as contracting. Financing contracting is particularly relevant if the capital from the investors is insufficient. Here, the contractor is paid based on performance from the operation of principal and interest, and the plant (i.e., the BESS) regularly becomes the property of the contractee by the end of the agreement. If plant contracting is employed, the contractor builds and operates the BESS, and it remains in his property throughout the utilization period. Plant contracting is, therefore, a feasible approach for all parties.

The effect to any end users is only the level of the physical supply of electricity and, whenever they act as PVOs, the additional power purchase. Therefore, new power supply contracts are established with power customers in the grid area of the operating ESC. Furthermore, there is the possibility that an electricity tariff is attached to the SOC of the MP-BESS and/or grid load, which results in high PV self-consumption on site and probably the best-suited grid relief method among the three models.

Again, the services and their cash flows of the ESC meet the model above (1-6), as presented in Figure 80. The type of line corresponds to the previous models. The power supply of the PVOs (7) and any end users (11) leads to additional revenues for the ESC (8 and 12), but the conditions may vary. The possibility exists that the contracts between the PVOs and the ESC may also include PV power purchases. This agreement allows the PVOs to store PV surplus energy (9), use a part of it and sell the remainder to the ESC (10).

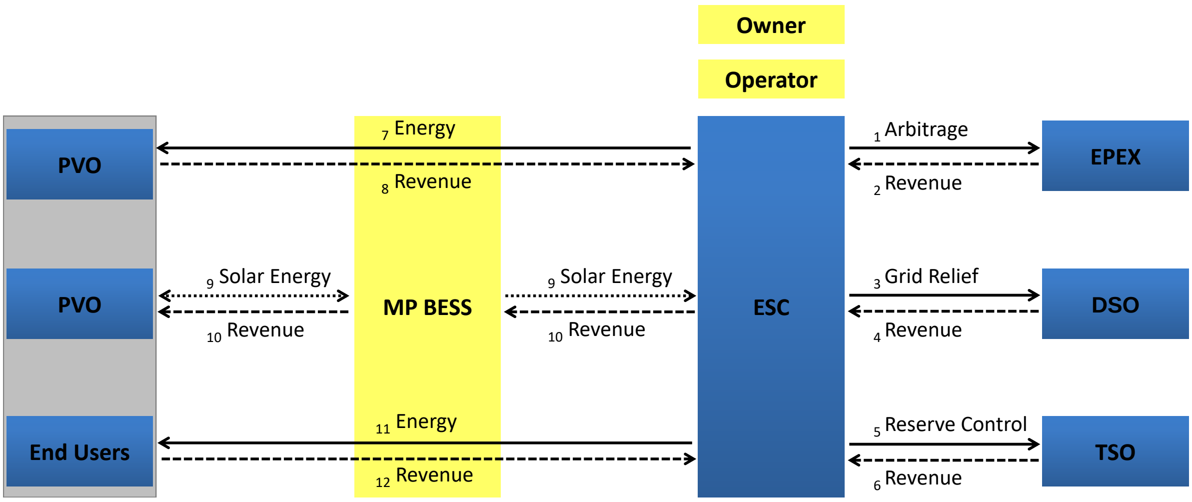

Figure 80 - ETM: Flows of cash, goods and services.

6.2 Evaluation of the Proposed Business Models

This chapter contains an evaluation of the proposed business models based on their marketability and feasibility. However, proper financial plans for all three business models are not available because they depend on multiple parameters, including the following:

- Investment costs
- Service costs
- Trade volume and revenue power exchange
- Trade volume and income control reserve
- Demand for grid relief
- Amount and load profile consumers
- Amount and load PV systems
- Electricity prices
- Feed-in remuneration

Thus, an accurate determination of the flows of cash, goods, and services is not possible. Because of the number of parameters and their individual ranges, the results of a broad sensitivity analysis may be unsatisfying. Nevertheless, the differences in the total revenues between the models are only marginal. The choice of one model depends on whether the priority is a benefit to the ESC or the customer, regarding business management or terms of the national economy. With the community battery storage business model, the cooperative takes the investment, and the ESC provides the services and acts as the operator. This model seems to be the most economical for residents who hold shares of the MP-BESS. Despite the dependence of the mentioned parameters and the investment risk, the highest ROI is possible for participating residents in the immediate grid area. The will to invest and the affordability are important. However, investment in renewables is popular with population masses in general as several studies have shown [230, 231]. Since the commencement of the Renewable Energy Sources Act in 2000, the total investment amount in renewable energy plants in Germany has been more than 200 billion euros [230], and the amount was the same worldwide for the year 2015 [231]. The motivations to finance and invest in renewable sources are similar to the reasons for investing in BESS [232]. The crucial motivations behind investment in BESS are to hedge against rising electricity prices and to contribute to the energy transition [233]. Residents want to invest as long as they can afford a share of the cooperative, i.e., the MP-BESS. Furthermore, this model is well suited for ESCs because of the modest risk with a chance for high revenue. The profit sharing concerning the services provides a strong incentive for the ESC.

The lease model excludes power costumers without a PV system, but it seems to be beneficial for PVOs and ESCs. In this case, the ESC bears the investment risk. Even if there is insufficient interest in leasing, the cash flow from the operating activities (arbitrage, grid relief, and control reserve) alone should lead to a positive ROI. Nevertheless, the success of leasing will depend on the commissioning time of the solar power plants and individual electricity costs in a broad sense. Therefore, the contribution margin from the differences in electricity costs and feed-in remuneration is important. The net present value of leasing an MP-BESS must be, at least, equivalent to one of the home storage systems to be of interest to PVOs.

The ETM could provide the best contribution to the energy transition in Germany because of the power customers, ESCs, and DSOs benefit, which makes this model the most grid-friendly type of BESS operation. Irrespective of unbundling provisions, this model could lead to a win-win situation for ESCs and DSOs in vertically integrated companies covering both fields. Additionally, this model is the most customer-friendly regarding effort and knowledge. Nevertheless, the success of this business model depends on power customer acceptance and will to change the ESC. With approximately 40 million households [234] and an ESC changing rate of approximately 9% in this consumer group [235], there is significant theoretical potential in Germany to acquire customers for an electricity tariff attached to the BESS. Furthermore, the topic of renewable energies is beneficial for electricity purchases because of the increasing demand and willingness to pay for ecologically certified power [232]. Since the stated MP-BESSs show network coupling without any direct connection to the respective PV system, as opposed to home storage systems, the final consumer must pay the full apportionment for renewables ("EEG-Umlage") and several other taxes and duties [73]. The allocations and costs considering the network charges are notable. Therefore, the ROI of self-consumption decreases with the contemplated BESS. Nevertheless, the possibility of individual network charges exists under § 19 German Electricity Network Fee Regulation Ordinance (StromNEV). With a demand of 10 GWh over a period of at least 7,000 hours per year [236], the fee is significantly lower and the overall ROI much higher. Relieving grid overloads, providing control reserve and arbitrage at the energy exchange generate substantial additional revenues that will outstrip the additional cost. The mentioned APMs lead to an overall increase in ROI. In this respect, economies of scale in investment costs are also notable. An overall decision of all business models is the purchase and sale of solar power. Under § 80 of the Renewable Energy Sources Act (EEG), a prohibition of multiple sales limits the possibilities of the ESC. The purchase price is equivalent to the feed-in remuneration, even if non-promoted direct marketing is the case. Therefore, an ecologically certified power sale after storage is possible if PVOs do not claim the feed-in remuneration beforehand, as per §§ 78-80 EEG, which raises the question of whether the purchase should be directed or PVOs should claim government incentives. No clear preference arises, especially if the sold power is classified as a regional product. Nevertheless, this is a short-term decision for one month, as per § 20 EEG. Finally, non-promoted direct marketing is a feasible option for sale and is economically beneficial [237]. The problem is that the grid operators are unable to directly participate in the BESS because of legal provisions concerning unbundling, which indicates that a grid-friendly and/or system-friendly operation depends only on the available cash flow. Thus, no preference for one of the alternatives is given. The UK Power Networks had a slightly different approach for their own business models. First, they distinguish between distribution network operators (DNOs) and DSOs. Second, the DNO builds, owns and operates the MP-BESS as an asset to the grid. Thus, certain stated services depend on contracts to the market or a third party. This arrangement again has problems with unbundling requirements, which are calculated with class and individual exemptions.

The established business models are only an overview of the options based on the status quo. There is no certainty that these business models in the respective constellation could withstand a legal review. This work notes the current possibilities for MP-BESS, but this work should also lead to investigations of additional business models. However, considering the marketability of at least one business model, expert interviews should lead to preference. Therefore, a consultation with representatives from economic and legal fields is appropriate. From a legal point of view, all three business models are feasible. In contrast, economic consideration by DSOs and ESCs excludes the ETM under the current framework conditions. The other two models are preferred based on public acceptance of the MP-BESS. Nevertheless, the operating ESC is willing to participate in community battery storage if profit sharing is the case and if they are granted a share of at least 51% of the cooperative. The ESC has the entrepreneurial decision. Considering the transaction costs of the ESC, the community battery storage model is the most feasible approach of the three business models.

Table 23 - Evaluation of the three business models, community battery storage (CES), lease model (LM) and ETM, by experts. The statements are only indicative assessments.

	CES	LM	ETM
DSO	+	+	+ / o
ESC 1	++	+	+ / o
ESC 2	++	+	+ / o
Lawyer	+	+	+

There is a consensus amongst all parties that storing surplus PV energy in a stationary BESS located within the grid is barely profitable considering the current framework conditions. Taxes, apportionments, and levies on stationary BESS located within the grid lead to additional costs and a potentially negative ROI. Furthermore, there is a consensus that grid relieving is not ideal without the participation of the DSO. In this context, it is important to ensure the legal provisions concerning unbundling.

6.3 Conclusion

In this chapter, the regulatory and legal influences in Germany on BESSs were investigated. Because of technical (as opposed to economic and legal) conditions, BESSs are a part of the successful energy transition in Germany. Peak shaving or peak shifting of renewable energy to reduce the changing load flow between grid levels is a feasible approach for BESSs.

In this regard, small-scale home storage systems have been introduced to the German and worldwide market, but they have not shown significant profitability. Considering the economies of scale, large stationary LIB BESSs will show profitability in certain applications, and they are currently profitable (as of 09/2016) as a PCP in Germany. However, a positive net value does not occur in most cases without the stacking of applications.

Therefore, multi-use, multi-system, and multi-purpose BESSs were compared and evaluated with regard to increasing the utilization ratio of the operation. Chapter 6 shows that multi-purpose BESSs can enhance the cost-effectiveness of the system.

Although there are a variety of applications for stationary BESSs, the exclusive use of a specific application is only rarely profitable under the current framework conditions. Rather, a combination of storing surplus PV energy, relieving grid overloads, arbitrage at the 15-minute intraday continuous market and providing negative SCP at low tariff is the most reasonable approach.

Matching these possibilities consecutively results in a comparison of the three theoretical business models: community battery storage, leasing, and ETMs. Each of these models has different advantages and disadvantages for the respective stakeholders. Table 24 gives a brief overview of a subjective evaluation of the three business models. Because the various pros and cons depend on the operation strategy and the model, the ratings are based on the likelihood of these strategies within the business models.

Table 24 - Evaluation of the three business models, community battery storage (CES), lease model (LM) and ETM, considering the most important stakeholders of the MP-BESS and individual implementation likelihood by experts. The statements are only indicative assessments.

	CES	LM	ETM
DSO	++	+	+ / o
End users	+ / o	o	+
ESC	++	+	+ / o
Municipality	+	+	+
PVO	+	+ / o	+ / o
TSO	+ / o	+ / o	+ / o

Because of a lack of public expertise, the energy supply company always provides any services, including the operation of BESSs. In community battery storage and in the lease and ETMs, the cooperative and the energy supply company, respectively, bear the investment risk for BESSs.

Therefore, different operational strategies appear, and TSOs, DSOs, and municipalities have no direct influence. A grid-friendly and/or system-friendly operation depends on the available cash flows in the respective markets. For the municipality, the concession and commercial tax amount are the same irrespective of the model.

The community battery storage offers an opportunity for a high investment return for PV system operators, any members of the cooperative and the energy supply company as a service provider. PV system operators and end users generate revenue by leasing parts of the BESS to the energy supply company and by redirection of the service cash flows. Additionally, cost savings occur via an increasing SCP of the PV system operators. Finally, the cooperative remunerates the service provider (energy supply company). The overall efficiency may increase with profit sharing of these services.

The lease model excludes end users from participating in BESS in any way. The energy supply company combines property and operation, and PV system operators can lease parts of BESS. Depending on the feed-in remuneration and individual power price, cost savings occur by increasing the SCP of the PV system operators. The energy supply company generates a return on their investment by keeping the service cash flows and the lease income.

The ETM presents the merger of possession, property, and operation of the energy supply company. Therefore, this model is legally classified as contracting. The energy supply company generates an ROI by keeping the service cash flows and the sale of electricity. Any customers of the energy supply company located in the grid area of the BESS have the option to choose a special electricity tariff attached to the MP-BESS. Reduced electricity costs will occur regardless of the operation of a solar power plant. If the tariff is connected to the SOC of the MP-BESS and/or grid load, an additional benefit for the grid and the system results.

Despite a thorough examination of the regulatory status quo and a comparison of the three models, no clear preference was derived regarding marketability. Nevertheless, the stated and further business models are expected to be economically feasible shortly because BESS investment prices and feed-in remuneration are decreasing as electricity prices increase. Therefore, this work notes some of the current possibilities for MP-BESSs, including the stated APM in LV grids, but further business models should be investigated. In addition, it should be emphasized that research and openly communicated business model evaluations are lacking in the field of MP-BESSs. Multiple use, multipurpose operation, or stacking of applications is performed to develop a temporarily working business case, gain customers and neglect the necessity for regulatory and jurisdictional assessments of the matter. Politicians, regulators and market participants are urged to review BESSs as an MPT.

7 Conclusions and Future Work

To conclude the thesis, "*Stationary Lithium-Ion Battery Energy Storage Systems: A Multi-Purpose Technology,*" the main findings are summarized, and the major findings and results are given. Additionally, in Subchapter 7.2, a brief outlook is provided.

7.1 Concluding Summary

In Chapter 1, the fundamental core issues that were investigated in this thesis were placed in a broader context, and the core issues are *the energy transition worldwide* and *interpreting LIB BESSs as an MPT carrier*. In the literature, BESSs are typically considered a single purpose technology with a specific application in a specific environment, but in recent literature, a shift toward a multi-purpose technology interpretation of BESS is identified.

The basis of BESSs technology was presented in Chapter 2. Aside from the definition of different SES technologies, which consider the overall characteristics, battery technology, i.e., LIB was introduced in detail, and all the necessary steps from a single component to the installation of a complete system were given. As a part of this introduction, the system safety of respective BESSs was put into perspective, and the legal framework was identified as a crucial point for successful economic BESS operation and installation. A stakeholder analysis for Germany showed which participants play a role in planning, building, operating and decommissioning BESSs.

The hypothesis, defining BESSs as an MPT carrier, which was further discussed in the thesis, was examined in Chapter 3 by providing a comprehensive review of possible applications for BESS. The focus was laid on the APMs most discussed in the literature and industry. These APMs, which are all single tasking, range from small residential storage up to several MWh storages in island grids or providing ancillary services.

The main part of the thesis, "*Stationary Lithium-Ion Battery Energy Storage Systems: A Multi-Purpose Technology,*" (Chapters 4, 5, and 6) was structured around two core issues. To establish an *investigation of the technical and legal functionalit*y of BESS and their suitability for becoming an MPT carrier to overcome *missing economic value*, the first part covered in detail excursuses and case studies and provided a broader and more fundamental understanding of BESSs *operating* in different APMs. The *technical functionality* of BESSs as an MPT carrier, i.e., MP-BESSs, was discussed and presented. Further, the second core issue discussed business models for the previous findings to accumulate ideas for a *proper legal framework* to operate an MP-BESS. As the respective chapters all ended with a conclusion, the results are given in the short form.

On the core issue of missing economic value → Solution approach: Multi-Purpose Use

- LIB BESSs currently lack economic positive figures for nearly any APM (as of 11/2016). This statement holds true for Germany, most of the EU, and large parts of the world because of their high CAPEX burden in economic business cases.

- However, a dramatic decrease in cost for LIB BESSs has been observed. This decrease will influence the aforementioned dramatically in the near future, and LIB BESSs will play a major role in modern grid evolution and the second electrification wave worldwide.
- The OPEX of LIB BESSs include materials, services and other costs to guarantee full operation and are burdened with the high capacity fade of LIB technology, which adds to the vast OPEX cost that must be included in business cases. The cost makes LIB BESSs even less attractive.
- LIB BESSs operating under a single APM, which accounts for the vast majority of LIB BESSs installed in the grid worldwide, yield low capacity factors, or utilization ratios, because of low daily usage and intensity of use.
- Therefore, LIB BESSs, operating as an MPT carrier, as proposed by this thesis, i.e., MP-BESSs, show increasing capacity factors and increasing revenue possibilities. The simple addition of secondary, minute or quaternary APMs on BESSs add significant economic value, and the CAPEX remain similar.
- LIB BESS aging by adding APMs seems to decrease for the investigated LIB chemistry. These results must be proven in the future using additional LIB chemistry simulations; however, the conclusion holds true for NMC and LFP LIB.

On the core issue of a proper legal framework → Solution Approach: Opening of regulations

- LIB BESSs operate under severe legal restrictions, which limits their theoretical economic value dramatically. This statement holds true for Germany, several European states, and most states worldwide.
- LIB BESSs defined as an MPT carrier offer an intensive tool for a multitude of stakeholders in any electricity business area, end consumers, grid operators, supply companies, power customers, transmission grid operators, municipalities and additional groups.
- LIB BESSs under the legal framework of a community battery storage are the most promising candidates for future implementation and large roll-out of LIB systems when legal framework and regulations are adopted accordingly.
- LIB BESSs under the legal framework of a lease model must figure in severe restrictions for unbundling electricity services in many areas, hindering future implementation.
- LIB BESSs under the legal framework of the ETM have been viewed by experts as an attractive model; however, such operation would induce similar regulatory changes as the lease model.

To support the profitability of LIB BESSs and make the technology accessible to anyone, BESSs have to be explained and viewed as MPT technology, not only by knowledge carriers, i.e., scientists or industry experts, but also by the broad community of politicians, municipalities, legislators, regulators, international and national panels and the public.

Recommendations for Action

Finally, with regard to the hypothesis of this work, that LIB BESSs have yet to be defined as MPT carriers, the “*investigation of the technical and legal functionalit*y” toward the “*missing economic value,*” LIB BESSs are regarded as suitable for a series of future tasks in the energy transition worldwide; they are able to operate in nearly any task regarding the storage of electric energy without constraints. In contrast, legal and regulatory framework issues (which are present because of the number of stakeholders) constrain the economic realization of LIB BESS.

Here, the key is to communicate LIB BESS capabilities, educate technology novices about LIB behavior and the underlying technology, invest in research on new LIB chemistry technologies and build new legal entities and definitions to create certainty for rising markets and a shift in the worldwide use of energy. Further, with high priority, the legal and regulatory definitions of electricity storage in grids, especially LIB BESS, have to overcome their current hurdles and accelerate much faster as it is seen today. Most technical problems and issues have been overcome, LIB prices are decreasing, and consumers are more aware of the ecological and economic feasibility of LIB BESS. A suitable solution with high benefits to the general public, due to its multi-purpose functionality, set LIB BESS up to be a key in the solution of energy problems worldwide.

7.2 The Future of Electricity Markets

On the trends in the electricity market in Germany

The reduction of BESS investment prices and feed-in remuneration, as well as the increase in electricity prices, are conducive to the economical use of BESSs. Recent changes in the legal and regulatory framework conditions in Germany will facilitate market access for several APMs [238, 239]. The expansion of RETs results in temporarily fluctuating electricity production and a changing load flow between the grid levels. Thus, storing PV surplus energy and relieving grid overloads will play an increasingly important role in Germany in the near future to alleviate the imbalance between the north and south and between metropolitan and rural areas. In the context of changing legal and regulatory framework conditions, the Federal Ministry of Economics and Technology introduced the “electricity market 2.0” with a White Paper and the electricity market law [239]. Legal and regulatory uncertainties will be gradually reduced. The subject of storage systems will find its way into various laws. However, a statutory definition has failed to materialize. Certain changes favor the flexibility and ancillary services of BESSs. The shortening of tender submission periods and standby duration at the control reserve market are notable. According to [238], the Federal Ministry of Economics and Technology has considered trimming down the product time-slice of SCP to one hour or even 15 minutes instead of the HT and low tariff periods used currently (as of 11/2016). Furthermore, the tender period of SCP could change from weekly to daily. Both would be major steps toward profitable uses for BESSs and a solution to the divergent interests of APMs. On the other side, changing regulations regarding the battery SOC providing PCP could result in a preference for PCP over SCP. According to [137], the required SOC range for a BESS changed if it is based on the 15-minute criterion instead of the 30-minute criterion, particularly at a low ratio between the capacity and prequalified PCP power. With a proportion of 1.0 and the former criterion, the SOC must be 50%. When providing the energy reserve for 15 minutes, the range is approximately 25 to 75%. From 2021 on, there will be a fundamental change in the business models as the remuneration for existing renewable energy installations ends, and dramatic amounts of PV system power enter the German electricity markets. Therefore, particularly for existing PV systems, an alternative marketing for electricity production must be established. In this context, storage operators have the option to acquire PV surplus energy at a favorable price. Because of this fact and the further expansion of renewables, wholesale electricity market prices are decreasing. The principal characteristics of this market include the merit order effect and higher volatility in prices. In summary, all of these facts suggest economic operation of the MP-BESS with the specified APMs. Storing PV surplus energy, relieving grid overloads, providing control reserve and arbitrage at the 15 and 30-minute intraday continuous market are more attractive for BESSs, and the decreasing trend in investment costs should also be considered. In general, there is a need for a clear definition of storage and the reduction of complex levy and taxation structures in current legislation toward simpler and more adaptable ones.

On the trends in the electricity markets worldwide

Because of the similarity of the basic electricity market architecture around the world, the business models presented in this thesis could be of interest in countries other than Germany [240, 241]. Although the wholesale electricity market in Europe is similar to the one in the U.S., differences exist, such as ancillary services. Whereas the definition by the Union for the Coordination of the Transmission of Electricity (UCTE) includes three types of control reserves (namely, the primary, secondary and minute control reserve), the United States Federal Energy Regulatory Commission (FERC) considers a further subdivision (i.e., regulation, spinning, non-spinning, replacement and supplemental reserve). Therefore, different APMs appear to be useful. These specifications in the U.S. market are conducive to the economical operation of BESSs. In Europe in the UCTE, all stated business models can be implemented one by one because of the similarity of the markets. Particularly in countries with a high share of renewables and fluctuating electricity production or changing load flow between the grid levels, MP-BESSs are a feasible approach. However, the U.S., specifically the states of CA, MA, NYC, and TX, recently passed major renewable energy bills to realize the potential for electricity storage. The State of Charge Study by the Massachusetts Energy Initiative [169] outlined the incredible hurdles electric energy storage must currently overcome and noted that all other commodities of modern society, i.e., food, water, gasoline, oil and natural gas, are *commonly* stored goods. The study concludes that 1,766 MW of advanced electricity storage (*resources that can dispatch energy in seconds, provide energy from 15 minutes to over 10 hours and range from small home systems to utility-scale systems in the bulk power grid*) in the years 2017 to 2020 would yield an increase in the state's gross state product of 2.2 billion USD and an additional 250 million USD in grid savings. It can be expected that countries worldwide will reach a common level of understanding for the use of electricity storage and increase activities to form new markets and secure economic wealth and a greener future.

List of Abbreviations

AbLaV	ordinance on agreements concerning interruptible loads
ACER	agency for the cooperation of energy regulations
APM	application mode
AUX	auxiliary system component
BESS	battery energy storage system
BMS	battery management system
BMs	battery cell modules
BRs	battery module racks
BSC	black start capacity
CAES	compressed air energy storage
CAES-AA	advanced adiabatic compressed air energy storage
CAPEX	capital expenditure
CES	community battery energy storage system
CPC	cooperative patent classification system
CSG	community and grid services (APM)
DER	distributed energy resources
DG	distributed generation unit
DLC	double-layer capacitor
DOC	depth-of-cycle
DOD	depth of discharge
DSO	distribution grid operator
DSO	distribution system operators
EEG	renewable energy sources act
EES	electrical energy storage system
EEX	European energy exchange
EFB	empty fruit bunches
EMA	exponential moving average
EMS	energy management system
ENTSO-E	European network of transmission system operators for electricity / www.entsoe.eu
EnWG	German energy act

EOL	end of life
EPEX	European power exchange
ESC	energy supply company
ETM	electricity tariff model
FERC	United States federal energy regulatory commission / www.ferc.gov
FES	flywheel energy storage
FUS	fiber and shell
GPT	general-purpose technology
GRID	grid optimized application mode (APM)
HT	high tariff
HV	high voltage
ISO	independent system operator
KWK	combined heat and power act
LCOE	levelized cost of energy
LIB	lithium-ion battery / storage
LM	lease model
LPT	local power transformer
LT	low tariff
LV	low voltage
MP-BESS	multi-purpose stationary battery energy storage system
MPT	multi-purpose technology
MS-BESS	multi-storage battery energy storage system
MU-BESS	multi-use battery energy storage system
MV	medium voltage
NaS	sodium-sulfur energy storage
NERC	North American electric reliability corporation / www.nerc.com
PCP	primary control reserve / power (APM)
PE	power electronic device
POME	palm oil mill effluent
PV	photovoltaic
PVO	PV system operators
RES	residential energy storage
RET	renewable energy technology

ROI	return on investment
RTO	regional transmission organization
SCP	secondary control reserve / power (APM)
SCR	self-consumption rate
SEI	solid electrolyte interface
SELF	storing surplus PV energy (APM)
SMA	simple moving average
SMES	superconducting magnetic energy storage
SOA	safe operation area
SOC	state of charge
SOF	state of function
SOR	state of reliability
SOS	state of safety
SPT	single-purpose technology
SSR	self-sufficiency rate
StromNEV	electricity grid charges ordinance
StromNZV	electricity grid access ordinance
StromStG	electricity tax act
TCR	minute control reserve / power (APM)
TSO	transmission system operator
UCPTE	Union for the Coordination of Production and Transmission of Electricity
UCTE	Union for the Coordination of the Transmission of Electricity
XHV	extra-high voltage

List of Symbols

C_{BR_n}	capacity of a specific BR (number indexed)
C_{CSG}	capacity of all community and grid serving battery racks of a MP-BESS
C_{index}	cost of a electricity (type indexed)
t_{sunset}	daily time for sunset at a specific geopoint
DCR	direct consumption rate
E_{index}	energy (type indexed)
δ	frequency deviation
$P_{CSG_{lim}}$	maximum power available for CSG operation
γ	merit order function in the SCP market [vector of bids]
apt	number of apartments
n_{BR}	number of BRs (BR type indexed)
E_{off}	offered energy in the SCP bid
P_{off}	offered power in the SCP bid
P_{Stor}	overall MP-BESS power
$\mathrm{P}_{\mathrm{index}}$	power (type indexed)
P_{BR_n}	power of a specific BR (number indexed)
η_{BESS}	roundtrip efficiency of a BESS
η_{LIB}	roundtrip efficiency of a LIB
η_{PE}	roundtrip efficiency of a PE unit
η_{SYS}	roundtrip efficiency of auxiliary systems in a BESS
SCR	self-consumption rate
SSR	self-supply rate
t_{index}	specific time (indexed)
SOC	state of charge
$E_{SCP_{max}}$	total energy require to fulfill SCP market bid
θ	total number of applications
ϑ	total number of BESS
t_{ref}	total possible time of utilization
r_u	utilization ratio [%]
SCP_{act}	weekly SCP participation vector (binary)

List of References

[1] Meehl, G.A.; Stocker, T.F.; Collins, W.D.; Friedlingstein, P.; Gaye, A.T.; Gregory, J.M.; Kitoh, A.; Knutti, R.; Murphy, J.M.; Noda, A.: *Global climate projections,* In: *Climate change 3495*, pp. 747–845, 2007

[2] The World Bank: *Climate Change Knowledge Portal,* URL: http://data.worldbank.org/topic/climate-change, log-date: 2016-11-18

[3] Stern, N.H.; Peters, S.; Bakhshi, V.; Bowen, A.; Cameron, C.; Catovsky, S.; Di Crane; Cruickshank, S.; Dietz, S.; Edmonson, N.: *Stern Review: The economics of climate change*, Cambridge University Press Cambridge, 2006

[4] COMM/CLIMA/0002: *Paris Agreement - European Commission,* URL: https://ec.europa.eu/clima/policies/international/negotiations/paris/index_en.htm, log-date: 2016-11-07

[5] BMWI: *Erneuerbare Energien in Zahlen – Anteile erneuerbarer Energien am Endenergieverbrauch in Deutschland,* URL: http://www.umweltbundesamt.de/themen/klima-energie/erneuerbare-energien/erneuerbare-energien-in-zahlen, log-date: 2015-03-30

[6] Jernbaneverket og Statens vegvesen: *The Norwegian National Transport Plan,* URL: http://www.ntp.dep.no/, log-date: 2016-10-27

[7] Pieters, J.: *Article in Press – MPS want only zero emissions cars sold on Dutch market by 2025,* URL: http://nltimes.nl/2016/03/30/mps-want-only-zero-emissions-cars-sold-on-dutch-market-by-2025/, log-date: 2016-10-27

[8] Lambert, F.: *Tesla Model 3 Reservations,* URL: https://electrek.co/2016/05/18/tesla-model-3-reservations-cancellations-duplicates/, log-date: 2016-11-04

[9] Eurobserv'er: *Photovoltaic Barometer,* URL: http://www.eurobserv-er.org/photovoltaic-barometer-2016/, log-date: 2016-10-27

[10] gtmresearch: *U.S. Solar Market Insight.* 20, Online, 2016

[11] Andersson, G.; Donalek, P.; Farmer, R.; Hatziargyriou, N.; Kamwa, I.; Kundur, P.; Martins, N.; Paserba, J.; Pourbeik, P.; Sanchez-Gasca, J.; Schulz, R.; Stankovic, A.; Taylor, C.; Vittal, V.: *Causes of the 2003 Major Grid Blackouts in North America and Europe, and Recommended Means to Improve System Dynamic Performance,* In: *IEEE Transactions on Power Systems 20* (*4)*, pp. 1922–1928, 2005

[12] Pourbeik, P.; Kundur, P.S.; Taylor, C.W.: *The anatomy of a power grid blackout,* In: *IEEE Power and Energy Magazine 4* (*5)*, pp. 22–29, 2006

[13] Yin, Y.-h.; Guo, J.-b.; Zhao, J.-j.; BU, G.-q.: *Preliminary analysis of large scale blackout in interconnected North America power grid on August 14 and lessons to be drawn [J],* URL: https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/ar/AR-1165.pdf, log-date: 2016-12-26

[14] Union for the co-ordination of transmission of electricity: *System Disturbance on 4 November 2006,* URL: https://www.entsoe.eu/fileadmin/user_upload/_library/publications/ce/otherreports/Final-Report-20070130.pdf, log-date: 2016-10-27

[15] Müller, M.; Battenberg, A.: *EEBatt - Interdisziplinäre Energiespeicherforschung,* URL: http://www.eebatt.tum.de/startseite/, log-date: 2016-03-17

[16] Lipsey, R.G.; Bekar, C.; Carlaw, K.: *General purpose technologies and economic growth.* 315, MIT Press, Cambridge, Mass, 1998

[17] Griliches, Z.: *Hybrid Corn – An Exploration in the Economics of Technological Change,* In: *Econometrica 25* (*4)*, p. 501–501, 1957

[18] Williamson, O.E.: *Credible commitments: Using hostages to support exchange,* In: *The American Economic Review 73* (*4)*, pp. 519–540, 1983

[19] David, P.A.: *The dynamo and the computer: an historical perspective on the modern productivity paradox,* In: *The American Economic Review 80* (*2)*, pp. 355–361, 1990

[20] Bresnahan, T.; Trajtenberg, M.: *General Purpose Technologies "Engines of Growth?",* In: *Journal of econometrics 65* (*1)*, pp. 83–108, 1992

[21] Battke, B.; Schmidt, T.S.: *Cost-efficient demand-pull policies for multi-purpose technologies – The case of stationary electricity storage – The Case of Stationary Electricity Storage,* In: *Applied Energy 155*, pp. 334–348, 2015

[22] Dolata, U.: *Technological innovations and sectoral change,* In: *Research Policy 38* (*6)*, pp. 1066–1076, 2009

[23] Wicklein, R.C.: *Designing for appropriate technology in developing countries,* In: *Technology in Society 20* (*3)*, pp. 371–375, 1998

[24] Technische Universität München: *Energy Neighbor – Research Project TUM,* URL: www.energyneighbor.de, log-date: 2016-03-08

[25] Technische Universität München: *EEBatt - Interdisziplinäre Energiespeicherforschung,* URL: http://www.eebatt.tum.de/startseite/, log-date: 2016-12-18

[26] Naumann, M.; Karl, R.C.; Truong, C.N.; Jossen, A.; Hesse, H.C.: *Lithium-ion Battery Cost Analysis in PV-household Application,* In: *Energy Procedia 73*, pp. 37–47, 2015

[27] International Electrotechnical Commission: *White Paper: Electrical Energy Storage.* 78, 1st edition, IEC, Switzerland, 2011

[28] TEPCO: *Challenges of TEPCO – The TEPCO Group's Environmental Initiatives,* URL: http://www.tepco.co.jp/en/challenge/csr/initiatives/index-e.html, log-date: 2016-11-07

[29] Kedzierski, M.A.; Payne, W.V.; Skye, H.M.: *Potential Research Areas in Residential Energy Storage for NIST's Engineering Laboratory – Potential Research Areas in Residential Energy Storage for NIST's Engineering Laboratory.* 34, National Institute of Standards and Technology, 2014

[30] International Renewable Energy Agency (IRENA): *Renewable Energy Cost Analysis: Hydropower* (*3),* 2012

[31] Luo, X.; Wang, J.; Dooner, M.; Clarke, J.: *Overview of current development in electrical energy storage technologies and the application potential in power system operation,* In: *Applied Energy 137*, pp. 511–536, 2015

[32] Islam, S.M.: *Increasing Wind Energy Penetration Level by Using Pumped Hydro Storage in Island Micro-Grid System,* In: *International Journal of Energy and Environmental Engineering 3* (*1)*, p. 9–9, 2012

[33] Havel, T.F.: *Adsorption-Enhanced Compressed Air Energy Storage,* URL: http://www.nsti.org/publications/Nanotech/2011/pdf/655.pdf, log-date: 2016-07-29

[34] Barton, J.P.; Infield, D.G.: *Energy Storage and Its Use With Intermittent Renewable Energy,* In: *IEEE Transactions on Energy Conversion 19* (*2)*, pp. 441–448, 2004

[35] Schaber, C.; Mazza, P.; Hammerschlag, R.: *Utility-Scale Storage of Renewable Energy,* In: *The Electricity Journal 17* (*6)*, pp. 21–29, 2004

[36] Béguin, F.; Raymundo-Piñero, E.; Frackowiak, E.: *Electrical Double-Layer Capacitors and Pseudocapacitors,* In: Gogotsi, Y.; Presser, V. (eds.): *Carbon Nanomaterials, Second Edition*, CRC Press, 2013

[37] Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y.: *Progress in electrical energy storage system – A critical review,* In: *Progress in Natural Science 19* (*3)*, pp. 291–312, 2009

[38] Fuchs, G.; Lunz, B.; Leuthold, M.; Sauer, D.U.: *Technology Overview on Electricity Storage – Overview on the potential and on the deployment perspectives of electricity storage technologies.* 66, Berlin, 2012

[39] Müller, M.; Viernstein, L.; Truong, C.N.; Eiting, A.; Hesse, H.C.; Witzmann, R.; Jossen, A.: *Evaluation of grid-level adaptability for stationary battery energy storage system applications in Europe,* In: *Journal of Energy Storage 9*, pp. 1–11, 2017

[40] Jossen, A.; Weydanz, W.: *Moderne Akkumulatoren richtig einsetzen.* X, 284 S., 1st edition, Reichardt Verlag, Neusäß, 2006

[41] Dong, D.; Wang, P.; Qin, W.; Han, X.: *Investigation of a microgrid with vanadium redox flow battery storages as a black start source for power system restoration,* In: *Conference onIndustrial Electronics and Applications (ICIEA) 9*, pp. 140–145, 2014

[42] Rand, D.A.J.; Moseley, P.T.; Garche, J.: *Valve-regulated Lead–Acid Batteries.* 606, Elsevier, 2004

[43] Sandia National Laboratories: *DOE Global Energy Storage Database,* URL: http://www.energystorageexchange.org/, log-date: 2016-11-07

[44] Nykvist, B.; Nilsson, M.: *Rapidly falling costs of battery packs for electric vehicles,* In: *Nature Climate Change 5* (*4)*, pp. 329–332, 2015

[45] Mueller, S.C.; Sandner, P.G.; Welpe, I.M.: *Monitoring innovation in electrochemical energy storage technologies – A patent-based approach,* In: *Applied Energy 137*, pp. 537–544, 2015

[46] Engelmann, J.; Brand, M.; Müller, M.; Kießling, S.: *Grundlagen von Batteriemanagementsystemen und deren funktionelle und strukturelle Evaluierung,* Forschungsarbeit, Technische Universität München, München, 2014

[47] Cabrera-Castillo, E.; Niedermeier, F.; Jossen, A.: *Calculation of the state of safety (SOS) for lithium ion batteries,* In: *Journal of Power Sources 324*, pp. 509–520, 2016

[48] Lu, L.; Han, X.; Li, J.; Hua, J.; Ouyang, M.: *A review on the key issues for lithium-ion battery management in electric vehicles,* In: *Journal of Power Sources 226*, pp. 272–288, 2013

[49] Lee, M.; Lee, J.; Lee, I.; Lee, J.; Chon, A.: *Wireless battery management system: 2013 World Electric Vehicle Symposium and Exhibition (EVS27)*

[50] Marzband, M.; Azarinejadian, F.; Savaghebi, M.; Guerrero, J.M.: *An Optimal Energy Management System for Islanded Microgrids Based on Multiperiod Artificial Bee Colony Combined With Markov Chain,* In: *IEEE Systems Journal*, pp. 1–11, 2015

[51] Reihani, E.; Sepasi, S.; Roose, L.R.; Matsuura, M.: *Energy management at the distribution grid using a Battery Energy Storage System (BESS),* In: *International Journal of Electrical Power & Energy Systems 77*, pp. 337–344, 2016

[52] Schuster, S.F.; Bach, T.; Fleder, E.; Müller, J.; Brand, M.; Sextl, G.; Jossen, A.: *Nonlinear aging characteristics of lithium-ion cells under different operational conditions,* In: *Journal of Energy Storage 1*, pp. 44–53, 2015

[53] Garche, J.; Moseley, P.T.; Adelmann, P. (eds.): *Electrochemical energy storage for renewable sources and grid balancing*, Elsevier, Amsterdam, Netherlands, 2015

[54] Daniel, C.; Besenhard, J.O.: *Handbook of Battery Materials.* 2027, 2nd edition, Wiley, Weinheim, 2012

[55] Balbuena, P.B.; Wang, Y.: *Lithium-ion batteries – Solid-electrolyte interphase.* 407, [Repr.], Imperial College Press, London, 2007

[56] Patil, A.; Patil, V.; Wook Shin, D.; Choi, J.-W.; Paik, D.-S.; Yoon, S.-J.: *Issue and challenges facing rechargeable thin film lithium batteries,* In: *Materials Research Bulletin 43* (*8-9)*, pp. 1913–1942, 2008

[57] Väyrynen, A.; Salminen, J.: *Lithium ion battery production,* In: *The Journal of Chemical Thermodynamics 46*, pp. 80–85, 2012

[58] Dinger, A.; Ripley, M.; Mosquet, X.; Russo, M.; Rabl, M.; Rizoulis, D.; Sticher, G.: *White Paper: Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020,* URL: https://www.bcg.com/documents/file36615.pdf, log-date: 2016-04-13

[59] Riegel, B.: *Anforderungen an Batterien für den stationären Einsatz,* In: Korthauer, R. (ed.): *Handbuch Lithium-Ionen-Batterien*, Springer Berlin Heidelberg, 2013

[60] Padhi, A.K.: *Phospho-olivines as Positive-Electrode Materials for Rechargeable Lithium Batteries,* In: *Journal of The Electrochemical Society 144* (*4)*, p. 1188–1188, 1997

[61] Terauchi, M.: *Sony's Lithium ion battery using olivine-type LFP cathode.* 8, Battery University, 2011

[62] Scrosati, B.; Garche, J.: *Lithium batteries – Status, prospects and future,* In: *Journal of Power Sources 195* (*9)*, pp. 2419–2430, 2010

[63] Buchmann, I.: *Lithium Titanate (Li4Ti5O12) – Batteryuniversity,* URL: http://batteryuniversity.com/learn/article/types_of_lithium_ion, log-date: 2016-08-09

[64] Miyaki, Y.; Hayashi, K.; Makino, T.; Yoshida, K.; Terauchi, M.; Endo, T.; Fukushima, Y.: *A Common Capacity Loss Trend – LiFePO4 Cell's Cycle and Calendar Aging: Honolulu PRiME*, Hawaii, 2012

[65] Doughty, D.H.; Crafts, C.C.: *FreedomCAR :electrical energy storage system abuse test manual for electric and hybrid electric vehicle applications.* 47, 2006

[66] Kerber, G.: *Report: Empfehlung zur Richtlinie zum Anschluss von Erzeugungsanlagen an das Niederspannungsnetz,* 2009

[67] Pinson, M.B.; Bazant, M.Z.: *Theory of SEI Formation in Rechargeable Batteries – Capacity Fade, Accelerated Aging and Lifetime Prediction,* In: *Journal of The Electrochemical Society 160* (*2)*, A243-A250, 2012

[68] BSW, BVES, DGS, StoREgio, ZVEH: *Sicherheitsleitfaden Li-Ionen Hausspeicher,* URL: https://www.solarwirtschaft.de/fileadmin/media/pdf/Sicherheitsleitfaden_Li-Ionen_Hausspeicher.pdf, log-date: 2016-11-07

[69] Vetter-Gindele, J.: *Geschäftsmodelle für stationäre fragmentierte Batteriespeicher,* Master Thesis, Technische Universität München, München, 2016

[70] Brahms, F.: *Stromspeicher im EEG 2014,* In: *ER EnergieRecht 2014* (*6)*, pp. 220–224, 2014

[71] Riewe, J.; Meyer, J.H.: *Stromspeicherdefinition im EnWG - Ein Werkzeugkasten aus rechtswissenschaftlicher Sicht,* In: *EWeRK 2015* (*3)*, pp. 138–144, 2015

[72] Bundesregierung Deutschland: *Entwurf eines Gesetzes zur Einführung von Ausschreibungen für Strom aus erneuerbaren Energien und zu weiteren Änderungen des Rechts der erneuerbaren Energien – EEG 2016,* URL: https://www.bmwi.de/BMWi/Redaktion/PDF/G/gesetzentwurf-ausschreibungen-erneuerbare-energien-aenderungen-eeg-2016,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, log-date: 2016-07-13

[73] Brahms, F.; Maslaton, M.: *Der Regierungsentwurf des Erneuerbaren-Energien-Gesetzes 2014 – Verfassungsrechtliche Bedenken gegen die EEG-Umlage auf die Eigenstromversorgung,* In: *NVwZ 2014* (*12)*, pp. 760–764, 2014

[74] *Energiewirtschaftsgesetz – EnWG,* 2005

[75] Richter, C.; Brahms, F.: *Rekommunalisierung von Strom- und Gasnetzen,* In: *KommJur 2014* (*1)*, pp. 6–13, 2014

[76] ENTSO-E: *Who Is ENTSO-E?,* URL: https://www.entsoe.eu/about-entso-e/Pages/default.aspx, log-date: 2016-06-16

[77] *Regulation (EC) No 713/2009 of the European Parliament and of the Council of 13 July 2009 establishing an Agency for the Cooperation of Energy Regulators – Regulation (EC) No 713/2009,* 2009

[78] *Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009 on conditions for access to the network for cross-border exchanges in electricity and repealing Regulation (EC) No 1228/2003 – Regulation (EC) No 714/2009,* 2009

[79] Berndt, H.; Hermann, M.; Kreye, H.D.; Reinisch, R.; Scherer, U.; Vanzetta, J.: *Report: TransmissionCode 2007 – Network and System Rules of the German Transmission System Operators*, Online, 2007

[80] Brahms, F.: *Der ENTSO-E Netzkodex für alle Netznutzer,* In: *ER EnergieRecht 2014* (*2)*, pp. 61–66, 2014

[81] *Directive No 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC – Directive No 2009/72/EC,* 2009

[82] Appen, J. von; Braun, M.; Stetz, T.; Diwold, K.; Geibel, D.: *Time in the Sun – The Challenge of High PV Penetration in the German Electric Grid,* In: *IEEE Power and Energy Magazine 11* (*2)*, pp. 55–64, 2013

[83] Oudalov, A.; Chartouni, D.; Ohler, C.; Linhofer, G.: *Value Analysis of Battery Energy Storage Applications in Power Systems: 2006 IEEE PES Power Systems Conference and Exposition, 2006 – PSCE '06 ; Oct. 29 2006 - Nov. 1 2006, [Sheraton Atlanta, Atlanta, Georgia, USA]*, IEEE Service Center, Piscataway, NJ, 2006

[84] Wrede, V.v.: *Die Transparenz im börslichen Stromgroßhandel am Beispiel der European Energy Exchange,* Zugl.: Köln, Univ., Diss., 2011. 180, 1. Aufl., Nomos, Baden-Baden, 2012

[85] Do, D.V.; Forgez, C.; El Kadri Benkara, K.; Friedrich, G.: *Impedance Observer for a Li-Ion Battery Using Kalman Filter,* In: *IEEE Transactions on Vehicular Technology 58* (*8)*, pp. 3930–3937, 2009

[86] BDEW: *Erneuerbare Energien und das EEG: Zahlen, Fakten, Grafiken (2015) – Anlagen, installierte Leistung, Stromerzeugung, EEG-Auszahlungen, Marktintegration der Erneuerbaren Energien und regionale Verteilung der EEG-induzierten Zahlungsströme,* Berlin, 11. Mai 2015, URL: https://www.bdew.de/internet.nsf/id/20150511-o-energie-info-erneuerbare-energien-und-das-eeg-zahlen-fakten-grafiken-2015-de/$file/Energie-Info_Erneuerbare_Energien_und_das_EEG_2015_11.05.2015_final.pdf, log-date: 2016-12-26

[87] Quaschning, V.: *Vergütung für Strom aus Photovoltaikanlagen nach dem Erneuerbare-Energien-Gesetz (EEG),* URL: http://www.volker-quaschning.de/datserv/EEG-PV/index.php, log-date: 2016-06-16

[88] *Gesetz für den Vorrang erneuerbarer Energien – EEG,* 2009

[89] *Gesetz für den Vorrang erneuerbarer Energien – EEG,* 2012

[90] Pawel, I.: *The Cost of Storage – How to Calculate the Levelized Cost of Stored Energy (LCOE) and Applications to Renewable Energy Generation,* In: *Energy Procedia 46*, pp. 68–77, 2014

[91] Megel, O.; Mathieu, J.L.; Andersson, G.: *Maximizing the potential of energy storage to provide fast frequency control,* In: *4th IEEE/PES innovative smart grid technologies Europe (ISGT Europe)*, pp. 1–5, 2013

[92] Zeh, A.; Müller, M.; Jossen, A.; Hesse, H.; Witzmann, R.: *Operating a Multitasking Stationary Battery Storage System for Providing Secondary Control Reserve on Low-Voltage Level,* In: *Proceedings of International ETG Congress 2015; Die Energiewende - Blueprints for the new energy age*, pp. 1–8, 2015

[93] Kairies, K.-P.; Haberschusz, D.; van Ouwerkerk, J.; Strebel, J.; Wessels, O.; Magnor, D.; Badeda, J.; Sauer, D.U.: *Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher – Jahresbericht 2016,*
URL: http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2016_Kairies_web.pdf, log-date: 2016-06-16

[94] RAP: *Netzentgelte in Deutschland: Herausforderungen und Handlungsoptionen – Studie im Auftrag von Agora Energiewende,* The Regulatory Assistance Project, 2014

[95] Statistisches Bundesamt: *Statistisches Jahrbuch – Deutschland und Internationales.* 693, Wiesbaden, 2015

[96] *Gewerbesteuergesetz – GewStG,* 2016

[97] Statistisches Bundesamt: *Hebesätze der Realsteuern – Ausgabe 2014 - Gemeinschaftsveröffentlichung,*
URL: https://www.destatis.de/DE/Publikationen/Thematisch/FinanzenSteuern/Steuern/Realsteuer/HebesaetzeRealsteuern.html, log-date: 2016-06-16

[98] *Verordnung über Konzessionsabgaben für Strom und Gas (Konzessionsabgabenverordnung) – KAV,* 1992

[99] EPRI, D.: *Electricity Energy Storage Technology Options – A White Paper Primer on Applications, Costs and Benefits,*
URL: http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001020676, log-date: 2016-12-26

[100] Eyer, J.; Corey, G.: *Energy storage for the electricity grid: Benefits and market potential assessment guide – A Study for the DOE Energy Storage Systems Program,* In: *Sandia National Laboratories 20* (*10)*, p. 5–5, 2010

[101] Hedegaard, K.; Meibom, P.: *Wind power impacts and electricity storage–A time scale perspective,* In: *Renewable Energy 37* (*1)*, pp. 318–324, 2012

[102] Lemaire, E.; Martin, N.; Nørgård, P.; Jong, E. de; Graaf, R. de; Groenewegen, J.; Kolentini, E.; Tselepis, S.: *European white book on grid-connected storage,* 2011

[103] Manz, D.; Keller, J.; Miller, N.: *Value propositions for utility-scale energy storage,* In: *Power Systems Conference and Exposition (PSCE)*, pp. 1–10, 2011

[104] Mariyappan, J.; Black, M.; Strbac, G.; Hemmi, K.: *Pushing a Least Cost Integration of Green Electricity into the European Grid–Cost and Technical Opportunities for Electricity Storage Technologies,* In: *Chineham, United Kingdom: IT Power,* 2004

[105] van der Linden, S.: *Bulk energy storage potential in the USA, current developments and future prospects,* In: *Energy 31* (*15)*, pp. 3446–3457, 2006

[106] Wassiliadis, N.: *Identifikation und Bewertung von Second Life Anwendungen für Fahrzeug-Traktionsbatterien,* Master Thesis, Technische Universität München, München, 2014

[107] Narula, C.K.; Martinez, R.; Onar, O.; Starke, M.R.; Andrews, G.: *Economic Analysis of Deploying Used Batteries in Power Systems – Report.* 122, Online, 2011

[108] Noce, C.; Riva, S.; Sapienza, G.; Brenna, M.: *Electrical energy storage in Smart Grid: Black-start study using a real-time digital simulator,* In: *IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG) 3*, pp. 216–220, 2012

[109] Battke, B.; Schmidt, T.S.; Grosspietsch, D.; Hoffmann, V.H.: *A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications,* In: *Renewable and Sustainable Energy Reviews 25*, pp. 240–250, 2013

[110] Fitzgerald, G.; Morris, J.; Mandel, J.: *The Economics of Battery Energy Storage – How multi-use, customer-sited batteries deliver the most services and value to customers and the grid,* URL: http://www.rmi.org/Content/Files/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf, log-date: 2016-03-08

[111] Malhotra, A.; Battke, B.; Beuse, M.; Stephan, A.; Schmidt, T.: *Use cases for stationary battery technologies – A review of the literature and existing projects,* In: *Renewable and Sustainable Energy Reviews 56*, pp. 705–721, 2016

[112] Bradbury, K.; Pratson, L.; Patiño-Echeverri, D.: *Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets,* In: *Applied Energy 114*, pp. 512–519, 2014

[113] Andresen, G.B.; Rodriguez, R.A.; Becker, S.; Greiner, M.: *The potential for arbitrage of wind and solar surplus power in Denmark,* In: *Energy 76*, pp. 49–58, 2014

[114] Cready, E.; Lippert, J.; Pihl, J.; Weinstock, I.; Symons, P.; Jungst, R.G.: *Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications – A Study for the DOE Energy Storage Systems Program.* 130, 2003

[115] E-Bridge; IAEW; OFFIS: *Moderne Verteilernetze für Deutschland – Verteilernetzstudie,* URL: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/verteilernetzstudie,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, log-date: 2016-12-26

[116] Pardatscher, R.: *Planungskriterien und Spannungsqualität in Mittel- und Niederspannungsnetzen mit hoher Photovoltaik-Einspeisung,* Techn. Univ., Diss. München, 2015. 138, Verlag Dr. Hut, München, 2015

[117] Zeh, A.; Witzmann, R.: *Operational Strategies for Battery Storage Systems in Low-voltage Distribution Grids to Limit the Feed-in Power of Roof-mounted Solar Power Systems,* In: *Energy Procedia 46*, pp. 114–123, 2014

[118] Castillo, A.; Gayme, D.F.: *Grid-scale energy storage applications in renewable energy integration – A survey,* In: *Energy Conversion and Management 87*, pp. 885–894, 2014

[119] Merei, G.; Moshövel, J.; Magnor, D.; Sauer, D.U.: *Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications,* In: *Applied Energy 168*, pp. 171–178, 2016

[120] Dena: *dena-Netzstudie II – Integration erneuerbarer Energien in die deutsche Stromversorgung im Zeitraum 2015 – 2020 mit Ausblick 2025.* 620, Berlin, 2010

[121] Wirth, H.: *Aktuelle Fakten zur Photovoltaik in Deutschland,* URL: www.pv-fakten.de, log-date: 2016-03-17

[122] Lödl, M.; Witzmann, R.; Metzger, M.: *Vergleich von Energiespeichern und Netzverstärkungsmaßnahmen in Niederspannungs-Verteilnetzen bei hoher dezentraler Einspeisung,* In: *VDE-Kongress 2010 E-Mobility,* 2012

[123] Kreditanstalt für Wiederaufbau - KfW: *KfW-Programm Erneuerbare Energien – Speicher (275)*, Frankfurt am Main, 2015

[124] Bayer, B.: *Demand Response - sind die USA ein Vorbild für Deutschland? Eine Analyse der Integration von Demand Response in die US-amerikanischen Kapazitäts- und Regelleistungsmärkte – Eine Analyse der Integration von Demand Response in die US-amerikanischen Kapazitäts- und Regelleistungsmärkte,* In: *IASS Working Paper,* 2014

[125] Deutsche Übertragungsnetzbetreiber: *Anforderungen an die Speicherkapazität bei Batterien für die Primärregelleistung,*
URL: https://www.regelleistung.net/ext/download/anforderungBatterien, log-date: 2016-12-26

[126] Koj, J.C.; Stenzel, P.; Schreiber, A.; Hennings, W.; Zapp, P.; Wrede, G.; Hahndorf, I.: *Life Cycle Assessment of Primary Control Provision by Battery Storage Systems and Fossil Power Plants,* In: *Energy Procedia 73*, pp. 69–78, 2015

[127] Stenzel, P.; Koj, J.C.; Schreiber, A.; Hennings, W.; Zapp, P.: *Primary control provided by large-scale battery energy storage systems or fossil power plants in Germany and related environmental impacts,* In: *Journal of Energy Storage 8* (*In Press, Corrected Proof)*, pp. 300–310, 2016

[128] Consentec GmbH: *Description of load-frequency control concept and market for control reserves,* Study commissioned by the German TSOs,
URL: https://www.regelleistung.net/ext/download/marktbeschreibungEn, log-date: 2016-12-26

[129] Regelleistung.net: *Gemeinsame Ausschreibung Sekundärregelleistung,*
URL: https://www.regelleistung.net/ext/static/srl, log-date: 2016-11-10

[130] Goebel, C.; Hesse, H.; Schimpe, M.; Jossen, A.; Jacobsen, H.-A.: *Model-based Dispatch Strategies for Lithium-Ion Battery Energy Storage applied to Pay-as-Bid Markets for Secondary Reserve,* In: *IEEE Transactions on Power Systems*, p. 1–1, 2016

[131] Regelleistung.net: *Gemeinsame Ausschreibung Minutenreserveleistung,* URL: https://www.regelleistung.net/ext/static/mrl, log-date: 2016-11-10

[132] Oudalov, A.; Cherkaoui, R.; Beguin, A.: *Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application,* In: IEEE (ed.): *2007 IEEE Power Tech*

[133] Leadbetter, J.; Swan, L.G.: *Selection of battery technology to support grid-integrated renewable electricity,* In: *Journal of Power Sources 216*, pp. 376–386, 2012

[134] Regelleistung.net: *Gemeinsame Ausschreibung Primärregelleistung,* URL: https://www.regelleistung.net/ext/static/prl, log-date: 2016-11-10

[135] UTCE: *Load-Frequency Control and Performance.* 33, Online, 2009

[136] Consentec GmbH: *Description of load-frequency control concept and market for control reserves – Study commissioned by the German TSOs,* URL: https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0ahUKEwiF8q71s5XRAhUB0SYKHUgyBJQQFggfMAA&url=https%3A%2F%2Fwww.regelleistung.net%2Fext%2Fdownload%2FmarktbeschreibungEn&usg=AFQjCNEgJb5rdXINHTe8HSUm5zuZzY7I5w&sig2=7qj9ItqzBapJZp_1XJxAuQ, log-date: 2016-12-26

[137] Zeh, A.; Müller, M.; Naumann, M.; Hesse, H.; Jossen, A.; Witzmann, R.: *Fundamentals of Using Battery Energy Storage Systems to Provide Primary Control Reserves in Germany,* In: *Batteries 2* (*3)*, p. 29–29, 2016

[138] Jawaid, H.; Ehsan, N.; Mirza, E.; Bhatti, M.W.: *Solar powered UPS,* In: *Procedia Technology 1*, pp. 217–224, 2012

[139] Aamir, M.; Ahmed Kalwar, K.; Mekhilef, S.: *Review – Uninterruptible Power Supply (UPS) system,* In: *Renewable and Sustainable Energy Reviews 58*, pp. 1395–1410, 2016

[140] Office, E.P.: *PATSTAT,* URL: https://www.epo.org/searching-for-patents/business/patstat.html#tab1, log-date: 2016-08-09

[141] Elsevier: *Scopus - Document search,* URL: https://www.scopus.com/, log-date: 2016-08-09

[142] Agora Energiewende: *Negative Strompreise: Ursachen und Wirkung – Eine Analyse der aktuellen Entwicklungen und ein Vorschlag für ein Flexibilitätsgesetz 2014,* 2014

[143] Office, E.P.: *Patent families,* URL: http://www.epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families.html, log-date: 2016-11-08

[144] Kleinknecht, A.; van Montfort, K.; Brouwer, E.: *The non-trivial choice between innovation indicators,* In: *Economics of Innovation and new technology 11* (*2)*, pp. 109–121, 2002

[145] Montecchi, T.; Russo, D.; Liu, Y.: *Searching in Cooperative Patent Classification: Comparison between keyword and concept-based search,* In: *Advanced Engineering Informatics 27* (*3)*, pp. 335–345, 2013

[146] European Patent Office: *Cooperative Patent Classification – Background,* URL: http://www.cooperativepatentclassification.org/about.html, log-date: 2016-11-08

[147] Office of the Chief Communications Officer: *USPTO and EPO Announce Launch of Cooperative Patent Classification System,* URL: http://www.uspto.gov/about-us/news-updates/uspto-and-epo-announce-launch-cooperative-patent-classification-system, log-date: 2016-08-09

[148] Archibugi, D.: *Patenting as an indicator of technological innovation – A review,* In: *Science and Public Policy 19* (*6)*, pp. 357–368, 1992

[149] Lanjouw, J.O.; Pakes, A.; Putnam, J.: *How to count patents and value intellectual property: The uses of patent renewal and application data,* In: *The Journal of Industrial Economics 46* (*4)*, pp. 405–432, 1998

[150] Harhoff, D.; Scherer, F.M.; Vopel, K.: *Citations, family size, opposition and the value of patent rights,* In: *Research Policy 32* (*8)*, pp. 1343–1363, 2003

[151] OECD: *Measuring Patent Quality – Indicators of Technological and Economic Value,* URL: https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=DSTI/DOC(2013)3&docLanguage=En, log-date: 2016-08-09

[152] Putnam, J.D.: *The Value of International Patent Rights.* 142, USA, 1996

[153] Albert, M.B.; Avery, D.; Narin, F.; McAllister, P.: *Direct validation of citation counts as indicators of industrially important patents,* In: *Research Policy 20* (*3)*, pp. 251–259, 1991

[154] Carpenter, M.P.; Narin, F.; Woolf, P.: *Citation rates to technologically important patents,* In: *World Patent Information 3* (*4)*, pp. 160–163, 1981

[155] Hirsch, J.E.: *An index to quantify an individual's scientific research output,* In: *Proceedings of the National Academy of Sciences of the United States of America 102* (*46)*, pp. 16569–16572, 2005

[156] Sidiropoulos, A.; Katsaros, D.; Manolopoulos, Y.: *Generalized Hirsch h-index for disclosing latent facts in citation networks,* In: *Scientometrics 72* (*2)*, pp. 253–280, 2007

[157] Guess, M.: *SoCal utility will buy 80MWh of battery storage from Tesla after methane leak,* URL: http://arstechnica.com/business/2016/09/socal-utility-will-buy-80mwh-of-battery-storage-from-tesla-after-methane-leak/, log-date: 2016-11-08

[158] Truong, C.; Naumann, M.; Karl, R.; Müller, M.; Jossen, A.; Hesse, H.: *Economics of Residential Photovoltaic Battery Systems in Germany – The Case of Tesla's Powerwall,* In: *Batteries 2* (*2)*, p. 14–14, 2016

[159] Hesse, H.C.; Naumann, M.; Müller, M.; Truong, N.; Schimpe, M.; Jossen, A.: *A Holistic Battery Storage Simulation Tool for Use Case Specific Cost Analysis,* 1st edition, München, 2016

[160] Marcus Müller: *Energy Storage as a Key Enabler of a New Electrification Wave – A Battery Storage Perspective*, Cambridge, MA, 2016

[161] Marcus Müller: *A German Perspective on Lithium-Ion Battery Technology*, State College, PA, USA, 2016

[162] Maik Naumann: *SimSES: Software zur techno-ökonomischen Simulation stationärer Energiespeicher*, Berlin, 2017

[163] Schmidt, J.P.; Weber, A.; Ivers-Tiffée, E.: *A novel and fast method of characterizing the self-discharge behavior of lithium-ion cells using a pulse-measurement technique,* In: *Journal of Power Sources 274*, pp. 1231–1238, 2015

[164] Rosenkranz, C.A.; Köhler, U.: *Modern Battery Systems for Plug-In Hybrid Electric Vehicles – Presentation,* 23rd International Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition (EVS-23), 2007

[165] Fürstenwerth, D.; Waldmann, L.: *Stromspeicher in der Energiewende – Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienstleistungen und im Verteilnetz, log-date:* 1/24/2015

[166] California ISO: *Q1 2016 Report on Market Issues and Performance.* 54, 2016

[167] Agora Energiewende: *Negative Electricity Prices: Causes and Effects – An analysis of recent developments and a proposal for a flexibility law.* 14, Berlin, 2014

[168] Turner, M.; Sinclair, D.: *Negative pricing in the GB wholesale electricity market.* 70, 6th edition, 2015

[169] Massachusetts Energy Storage Initiative: *State of Charge.* 271, 1st edition, Online, 2016

[170] Castillo-Cagigal, M.; Caamaño-Martín, E.; Matallanas, E.; Masa-Bote, D.; Gutiérrez, A.; Monasterio-Huelin, F.; Jiménez-Leube, J.: *PV self-consumption optimization with storage and Active DSM for the residential sector,* In: *Solar Energy 85* (*9)*, pp. 2338–2348, 2011

[171] Hoppmann, J.; Volland, J.; Schmidt, T.S.; Hoffmann, V.H.: *The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model,* In: *Renewable and Sustainable Energy Reviews 39*, pp. 1101–1118, 2014

[172] Leadbetter, J.; Swan, L.: *Battery storage system for residential electricity peak demand shaving,* In: *Energy and Buildings 55*, pp. 685–692, 2012

[173] Weniger, J.; Tjaden, T.; Quaschning, V.: *Sizing of Residential PV Battery Systems,* In: *Energy Procedia 46*, pp. 78–87, 2014

[174] Blechinger, P.; Seguin, R.; Cader, C.; Bertheau, P.; Breyer, C.: *Assessment of the Global Potential for Renewable Energy Storage Systems on Small Islands,* In: *Energy Procedia 46*, pp. 294–300, 2014

[175] Cha, S.T.; Wu, Q.; Zhao, H.; Wang, C.: *Frequency Control for Island Operation of Bornholm Power System,* In: *Energy Procedia 61*, pp. 1389–1393, 2014

[176] Franzen, E.; Strauch, N.; Triebel, C.: *Switching off the Generator – the Stable Operation of Sustainable Island Grids in the MW Range Using Renewable Energy and Energy Storage,* URL: http://www.credp.org/Data/YounicosRES_EN.pdf, log-date: 2016-12-26

[177] Vasconcelos, H.; Moreira, C.; Madureira, A.; Lopes, J.P.; Miranda, V.: *Advanced Control Solutions for Operating Isolated Power Systems – Examining the Portuguese islands,* In: *IEEE Electrification Magazine 3* (*1)*, pp. 25–35, 2015

[178] Netztransparenz: *EEG-Anlagenstammdaten Gesamtdeutschland zur Jahresabrechnung 2014,* URL: https://www.netztransparenz.de/de/Anlagenstammdaten.htm, log-date: 2016-01-20

[179] Transformers Committee of the IEEE Power Engineering Society: *IEEE Guide for the Evaluation and Reconditioning of Liquid Immersed Power Transformers.* 1 online resource, IEEE, Piscataway, NJ, USA, 2006

[180] Bundesverband der Energie- und Wasserwirtschaft e.V.: *Standardlastprofile Strom,* URL: https://www.bdew.de/internet.nsf/id/de_standartlastprofile, log-date: 2016-08-04

[181] Bundesverband der Energie- und Wasserwirtschaft e.V.: *BDEW-Strompreisanalyse Juni 2014 – Haushalte und Industrie,* URL: https://www.bdew.de/internet.nsf/id/20140702-pi-steuern-und-abgaben-am-strompreis-steigen-weiter-de/$file/140702%20BDEW%20Strompreisanalyse%202014%20Chartsatz.pdf, log-date: 2016-12-13

[182] Philipps, S.; Warmuth, W.: *Photovoltaics Report 2015,* URL: https://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf, log-date: 2016-08-04

[183] Thomas, G.: *Energiewende in Germany: from generation to integration.* 21, Online, 2014

[184] Parkinson, G.: *How far away is grid parity for residential battery storage?,* URL: http://reneweconomy.com.au/2014/how-far-away-is-grid-parity-for-residential-battery-storage-62637, log-date: 2016-12-10

[185] Greentech Media: *How Long Until Residential Battery Storage Reaches Grid Parity in Germany?,* URL: http://www.greentechmedia.com/articles/read/how-far-away-is-grid-parity-for-residential-battery-storage, log-date: 2014-08-26

[186] Weniger, J.; Bergner, J.; Tjaden, T.; Quaschning, V.: *Economics of Residential PV Battery Systems in the Self-Consumption Age,* 7 pages / 29th European Photovoltaic Solar Energy Conference and Exhibition; 3871-3877, 2014

[187] *Erneuerbare-Energien-Gesetz – EEG,* 2014

[188] Tjaden, T.; Bergner, J.; Weniger, J.; Quaschning, V.: *Repräsentative elektrische Lastprofile für Wohngebäude in Deutschland auf 1-sekündiger Datenbasis,* URL: https://pvspeicher.htw-berlin.de/veroeffentlichungen/daten/, log-date: 2017-03-17

[189] Mauch, W.; Mezger, T.; Staudacher, T.: *Anforderungen an elektrische Energiespeicher: Elektrische Energiespeicher – Schlüsseltechnologie für energieeffiziente Anwendungen ; Tagung, Fulda, 25. und 26. März 2009*, VDI-Verl., Düsseldorf, 2009

[190] German Transmission System Operators: *Eckpunkte und Freiheitsgrade bei Erbringung von Primärregelleistung,* URL: https://www.regelleistung.net/ext/download/eckpunktePRL, log-date: 2016-08-03

[191] Stich, J.; Hamacher, T.; Muller, M.; Hesse, H.C.; Jossen, A.: *Sustainable power supply options for large islands — A case study for Belitung Island – A case study for Belitung Island,* In: *Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, pp. 371–377, 2016

[192] Indonesian Government: *Sensus Penduduk 2010 - Indonesia,* URL: http://sp2010.bps.go.id/, log-date: 2016-08-16

[193] Menteri Energi Dan Sumber Daya Mineral: *Rencana umum Ketenagalistrikan Nasional,* URL: http://www.djk.esdm.go.id/pdf/Draft%20RUKN/Draft%20RUKN%202015%20-%202034.pdf, log-date: 2016-12-26

[194] Rokhidah, R.; Sukedi, S.: *Survei Sosial Ekonomi Nasional 2013 Kor Gabungan,* URL: http://microdata.bps.go.id/mikrodata/index.php/catalog/220, log-date: 2016-12-26

[195] EIA: *Assumptions to the Annual Energy Outlook 2014.* 197, Washington, D.C.

[196] Tidball, R.; Bluestein, J.; Rodriguez, N.; Knoke, S.: *Cost and Performance Assumptions for Modeling Electricity Generation Technologies,* In: *NREL Report SR-6A20-48595 1*, pp. 37–41, 2010

[197] Stich, J.; Mannhart, M.; Zipperle, T.; Massier, T.; Huber, M.; Hamacher, T.: *Modelling a Low-Carbon Power System for Indonesia, Malaysia and Singapore,* In: *33rd IEW International Energy Workshop 33,* 2014

[198] Battke, B.M.: *Multi-purpose technologies, lock-in and efficiency – Policy implications from the case of stationary electricity storage*, Zürich, ETH-Zürich, 2014

[199] Brehler, M.; Söllch, M.: *Erste Primärregelleistung durch privat genutze Schwarm-Stromspeicher – - Erfolgreiche Präqualifikation im Rahmen des Pilotprojekts SWARM - Beitrag zur Stabilisierung des Stromnetzes,* Gemeinsame Presseinformation der N-ERGIE Aktiengesellschaft und der Caterva GmbH, Nürnberg/Pullach, 2015

[200] Pudjianto, D.; Ramsay, C.; Strbac, G.: *Virtual power plant and system integration of distributed energy resources,* In: *IET Renewable Power Generation 1* (*1)*, p. 10–10, 2007

[201] Le Baron, D.: *New residential business models – From self-consumption to swarm grid services.* 35, München, 2015

[202] Klampt, W.: *Report: Sicherheits- und Performancetests Zelle – Project EEBatt.* 104, München, 2013

[203] Thomann, R.: *Strombank,* Kongress Energie- und Energiespeichertechnologien. 12, Stuttgart, 2014

[204] Esslinger, P.: *Entwicklung und Verfikation eines stochastischen Verbraucherlastmodells für Haushalte.* 21, Graz, 2012

[205] Zeh, A.; Rau, M.; Witzmann, R.: *Comparison of decentralised and centralised grid-compatible battery storage systems in distribution grids with high PV penetration,* In: *Progress in Photovoltaics: Research and Applications 24* (*4)*, pp. 496–506, 2016

[206] Müller, M.; Zeh, A.; Rohr, S.; Schuster, S.F.; Campestrini, C.; Hesse, H.; Witzmann, R.; Lienkamp, M.; Jossen, A.: *Evaluation of the Aging Behaviour of Stationary Lithium-Ion*

Battery Storage Systems for Different Photovoltaic-Driven Applications in low Voltage Grids, 7 pages / 31st European Photovoltaic Solar Energy Conference and Exhibition; 3084-3090, 2015

[207] Wohlfahrt-Mehrens, M.; Vogler, C.; Garche, J.: *Aging mechanisms of lithium cathode materials,* In: *Journal of Power Sources 127* (*1-2)*, pp. 58–64, 2004

[208] Keil, P.; Schuster, S.F.; Wilhelm, J.; Travi, J.; Hauser, A.; Karl, R.C.; Jossen, A.: *Calendar Aging of Lithium-Ion Batteries,* In: *Journal of The Electrochemical Society 163* (*9)*, A1872-A1880, 2016

[209] Keil, P.; Jossen, A.: *Calendar Aging of NCA Lithium-Ion Batteries Investigated by Differential Voltage Analysis and Coulomb Tracking,* In: *Journal of The Electrochemical Society 164* (*1)*, A6066-A6074, 2016

[210] Jossen, A.; Weydanz, W.: *Moderne Akkumulatoren richtig einsetzen – 36 Tabellen.* X, 284 S., 1. Aufl., Ubooks, Neusäß, 2006

[211] Fleckenstein, M.; Bohlen, O.; Bäker, B.: *Aging Effect of Temperature Gradients in Li-ion Cells,* In: *World Electric Vehicle Journal 5* (*1)*, pp. 322–333, 2012

[212] Ecker, M.; Gerschler, J.B.; Vogel, J.; Käbitz, S.; Hust, F.; Dechent, P.; Sauer, D.U.: *Development of a lifetime prediction model for lithium-ion batteries based on extended accelerated aging test data,* In: *Journal of Power Sources 215*, pp. 248–257, 2012

[213] Ecker, M.; Nieto, N.; Käbitz, S.; Schmalstieg, J.; Blanke, H.; Warnecke, A.; Sauer, D.U.: *Calendar and cycle life study of Li(NiMnCo)O2-based 18650 lithium-ion batteries,* In: *Journal of Power Sources 248*, pp. 839–851, 2014

[214] Marongiu, A.; Roscher, M.; Sauer, D.U.: *Influence of the vehicle-to-grid strategy on the aging behavior of lithium battery electric vehicles,* In: *Applied Energy 137*, pp. 899–912, 2015

[215] Herb, F.: *Alterungsmechanismen in Lithium-Ionen-Batterien und PEM-Brennstoffzellen und deren Einfluss auf die Eigenschaften von daraus bestehenden Hybrid-Systemen,* dissertation, Universität Ulm, Ulm, 2010

[216] Broussely, M.; Biensan, P.; Bonhomme, F.; Blanchard, P.; Herreyre, S.; Nechev, K.; Staniewicz, R.J.: *Main aging mechanisms in Li ion batteries,* In: *Journal of Power Sources 146* (*1-2)*, pp. 90–96, 2005

[217] Omar, N.; Monem, M.A.; Firouz, Y.; Salminen, J.; Smekens, J.; Hegazy, O.; Gaulous, H.; Mulder, G.; van den Bossche, P.; Coosemans, T.; van Mierlo, J.: *Lithium iron phosphate based battery – Assessment of the aging parameters and development of cycle life model,* In: *Applied Energy 113*, pp. 1575–1585, 2014

[218] E.ON Mitte AG: *Standardlastprofile 2012*, Kassel, 2014

[219] Zeh, A.; Witzmann, R.: *Combined operation of a battery storage system on distribution grid level – impact on the grid and economic benefit*, Lyon, 2015

[220] Lödl, M.; Kerber, G.; Witzmann, R.; Hoffmann, C.; Metzger, M.: *Abschätzung des Photovoltaik-Potentials auf Dachflächen in Deutschland*, Graz, 2010

[221] Lödl, M.; Witzmann, R.; Metzger, M.: *Operation strategies of energy storages with forecast methods in low-voltage grids with a high degree of decentralized generation,* In: *Electrical Power and Energy Conference*, pp. 52–56, 2011

[222] Notton, G.; Lazarov, V.; Stoyanov, L.: *Optimal sizing of a grid-connected PV system for various PV module technologies and inclinations, inverter efficiency characteristics and locations,* In: *Renewable Energy 35* (*2)*, pp. 541–554, 2010

[223] Hödel, P.: *Simulation und Optimierung eines multifunktionalen stationären Li-Ionen Batteriespeichers,* Master Thesis, Technische Universität München, München, 2016

[224] Klemisch, H.: *Genossenschaften in der Energiewirtschaft - Entwicklungen und Potenziale – Fachgespräch Friedrich Ebert Stiftung "Neue genossenschaftliche Betätigungsfelder" am 22.05.2012,*
URL: http://www.fes.de/wiso/pdf/mittelstand/2012/220512/Klemisch.pdf, log-date: 2016-06-16

[225] Staab, J.: *Erneuerbare Energien in Kommunen: Energiegenossenschaften gründen*, Springer Fachmedien, Wiesbaden, 2013

[226] Zantow, R.; Dinauer, J.: *Finanzwirtschaft des Unternehmens – Die Grundlagen des modernen Finanzmanagements,* 3., aktualisierte Aufl., Pearson Studium, München, 2011

[227] Flieger, B.: *Energiegenossenschaften – Eine klimaverantwortliche, bürgernahe Energiewirtschaft ist möglich*

[228] Schröder, C.; Walk, H.: *Genossenschaften und Klimaschutz*, Springer Fachmedien Wiesbaden, Wiesbaden, 2014

[229] Staab, J.: *Die 7 häufigsten Insolvenzgründe erkennen und vermeiden – Wie KMU nachhaltig erfolgreich bleiben*, Springer Gabler, Wiesbaden Germany, 2015

[230] BMWI: *Investitionen in Erneuerbarer Energien in Deutschland in den Jahren 2000 bis 2014 (in Milliarden Euro),*
URL: http://de.statista.com/statistik/daten/studie/171896/umfrage/investitionen-in-anlagen-zur-nutzung-von-strom-aus-erneuerbaren-energien/, log-date: 2016-06-16

[231] Bloomberg New Energy Finance: *Entwicklung der weltweiten Investitionen in Erneuerbare Energien in den Jahren 2004 bis 2015 (in Milliarden US-Dollar) – Global Trends in Renewable Energy Investment 2016 - Key Findings,*
URL: http://de.statista.com/statistik/daten/studie/180528/umfrage/entwicklung-der-investitionen-in-erneuerbare-energien-weltwei/, log-date: 2016-06-16

[232] Friege, C.; Herbes, C. (eds.): *Marketing Erneuerbarer Energien – Grundlagen, Geschäftsmodelle, Fallbeispiele*, Springer Gabler, Wiesbaden, 2015

[233] Kairies, K.-P.; Haberschusz, D.; Magnor, D.; Leuthold, M.; Badeda, J.; Sauer, D.U.: *Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher – Jahresbericht 2015,*
URL: http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2015_web.pdf, log-date: 2016-06-16

[234] Statistisches Bundesamt: *Bevölkerung und Erwerbstätigkeit – Haushalte und Familien,* Ergebnisse des Mikrozensus 2014, URL: https://www.destatis.de/DE/Publikationen/Thematisch/Bevoelkerung/HaushalteMikrozensus/HaushalteFamilien2010300147004.pdf?__blob=publicationFile, log-date: 2016-06-16

[235] BNetzA: *Monitoringbericht 2015,* Stand: 10.November 2015, URL: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Allgemeines/Bundesnetzagentur/Publikationen/Berichte/2015/Monitoringbericht_2015_BA.pdf?__blob=publicationFile&v=3, log-date: 2016-06-16

[236] *Stromnetzentgeltverordnung – StromNEV,* 2005

[237] *Gesetz für den Ausbau erneuerbarer Energien – EEG 2014,* 2014

[238] BMWI: *Entwurf eines Gesetzes zur Weiterentwicklung des Strommarktes (Strommarktgesetz) – Gesetzentwurf der Bundesregierung,* URL: http://www.bmwi.de/BMWi/Redaktion/PDF/E/entwurf-eines-gesetzes-zur-weiterentwicklung-des-strommarktes,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, log-date: 2016-06-16

[239] BMWI: *Ein Strommarkt für die Energiewende – Ergebnispapier des Bundesministeriums für Wirtschaft und Energie (Weißbuch),* URL: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/weissbuch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf, log-date: 2016-06-16

[240] Wilson, R.: *Architecture of Power Markets,* In: *Econometrica Vol. 70, No. 4 (July,2002)*, pp. 1299–1340, 2002

[241] Wang, Q.; Zhang, C.; Ding, Y.; Xydis, G.; Wang, J.; Østergaard, J.: *Review of real-time electricity markets for integrating Distributed Energy Resources and Demand Response,* In: *Applied Energy 138*, pp. 695–706, 2015

List of Appendices

A.1 PATSTAT CPC code for search query

Included Codes	
CPC subclass	Group(s) & subgroups
B60L	11/185%
B60L	11/186%
B60L	11/187%
B60H	1/00278
B60R	16/04
H01M	2%
H01M	10%
H01M	2200%
H01M	2220%
H02H	7/18
H02J	7%
Y02E	60/12%
Y02T	10/7005
Y02T	10/7011
Y02T	10/7016
Y02T	10/621%
Y02T	10/622%
Y02T	10/623%
Y02T	10/624%
Y02T	10/625%
Y02T	10/626%
Excluded Codes	
H02J	17%
H01M	12%
B60L	11/185

A.2 SCOPUS code for search query

```
(ALL(battery)
AND NOT KEY(primary)
AND TITLE-ABS-KEY("battery system")
OR TITLE-ABS-KEY("battery module")
OR TITLE-ABS-KEY("battery pack")
AND TITLE-ABS-KEY("secondary battery"))
AND PUBYEAR > 1989 AND PUBYEAR < 2016
AND ( LIMIT-TO(SUBJAREA,"ENGI" )
OR LIMIT-TO(SUBJAREA,"ENER" )
OR LIMIT-TO(SUBJAREA,"COMP" )
OR LIMIT-TO(SUBJAREA,"ENVI" )
OR LIMIT-TO(SUBJAREA,"MATH" ))
```

A.3 Purpose of Li-ion storage systems from data derived from DEO Database

Purpose of Li-ion storage systems	n	share
Renewable capacity firming	119	26.33%
Frequency regulation	105	23.23%
Electric bill management	101	22.35%
Electric energy time shift	99	21.90%
Onsite renewable generation shifting	75	16.59%
Renewables energy time shift	71	15.71%
Voltage support	70	15.49%
Electric bill management with renewables	50	11.06%
On-site power	49	10.84%
Grid-connected commercial (reliability & quality)	47	10.40%
Amount of Li-ion storage systems	452	100.00%

A.4 Number of Li-ion storage system projects per country from data derived from the DEO database

Country	n	share
United States	224	50%
China	50	11%
Korea, South	22	5%
Italy	20	4%
Netherlands	20	4%
Germany	19	4%
Japan	18	4%
United Kingdom	13	3%
France	10	2%
Spain	10	2%

A.5 Number of Li-ion storage system projects per continent from data derived from the DOE database

Continent	n	share
North America	239	53%
Europe	106	23%
Asia	95	21%
Others	13	3%

A.6 SOC heatmap of an MP-BESS operating CES (top) and an SOC heatmap of an MP-BESS operating CSG only (bottom)