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Samuli Kivipelto

GRID SCALE BATTERY ENERGY STORAGE INVESTMENT POTENTIAL

Analysis and Simulations of Frequency Control Markets in Germany and the UK

Master's Thesis in
Industrial Management

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FOREWORD

This study was carried out for and in close co-operation with Fortum Power and Heat Oy. I would like to express my deepest gratitude to the company, its trading and asset optimization unit (TAO) and all the colleagues who enabled the study and assisted throughout. Special recognition is addressed to my professional thesis instructor Roosa Nieminen and to my manager Tatu Kulla for the great opportunity and effective co-operation.

Disclaimer

This study does not include any market views or expectations from Fortum's behalf. The analyzed data and information is publicly available and all of the results and conclusions are solely based on author's own research contribution and subjective views.

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Samuli Kivipelto

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SYMBOLS AND ABBREVIATIONS

Symbols

A	AHP pairwise comparison matrix
A_{norm}	Normalized AHP pairwise comparison matrix
e_{ij}	AHP pairwise judgements between alternatives i and j in A
E_{ij}	Normalized AHP pairwise judgements between alternatives i and j
L_{mn}	Local AHP priority weight for alternative m in criteria n
LOGN[a,b]	Lognormal distribution: a= mean, b=standard deviation
N[a,b]	Normal distribution: a=mean, b=standard deviation
U[a, b]	Uniform distribution: a=minimum value, b= maximum value
W	Global AHP priority vector
w	Local AHP priority vector
λ_{max}	Maximum matrix eigenvalue

Abbreviations

AHP	Analytical Hierarchy Process
AS	Ancillary Services
BESS	Battery Energy Storage System
CAGR	Compound Average Growth Rate
CI	Consistency Index
CM	Capacity Market
CR	Consistency Ratio
DNO	Distribution Network Operator
EFR	Enhanced Frequency Response
ES	Energy Storage
FCF	Free Cash Flow
IRR	Internal Rate of Return
Li-ion	Lithium Ion
MCS	Monte Carlo Simulation
NPV	Net Present Value
OMR	Online Market Research
PBP	Pay Back Period
PCR	Primary Control Reserve
RES	Renewable Energy Source
TSO	Transmission System Operator
WACC	Weighted Average Cost of Capital

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Author:	Samuli Kivipelto
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ABSTRACT:

The need for energy storages in future power systems is acknowledged both in literature and in industry. Simultaneously battery energy storage technologies, especially Lithium-ion, are seen technologically relatively mature with favorable cost development. Whereas frequency control markets provide exploitable commercial and technical framework for battery investment. Nevertheless, true commercial viability is still uncertain in leading European markets in Germany and the UK.

The purpose of the study was to provide complete and comparative market analysis and demonstrated prospective investment profitability outcomes for grid scale battery energy storages in Germany and the UK. In addition, the study aimed to show required conditions for desired investment performances. The study explored investment potential in primary frequency control market in Germany and enhanced frequency response market in the UK by analyzing market attractiveness from multiple aspects. The countries were ranked based on the analyzed aspects by Analytical Hierarchy Process. Finally, financial Monte Carlo investment simulations with revenue and cost uncertainties were performed. Simulations also provided required conditions for profitability. Analyzed data was based on historical market data, performed online market research and literature.

Key findings of the study revealed that the chosen markets form suitable commercial framework for battery investments, but Germany shows clearly higher potential. However, the potential was questionable since both markets face significant challenges especially in financial sense. The concerns were confirmed by the simulations which suggested around 1–5 % and -3–3 % internal rate of return levels for Germany and the UK respectively. In addition, reaching 6 % return was seen very challenging whilst over 10 % return levels seemed unrealistic in the UK and extremely optimistic for Germany. The overall conclusion was that battery energy storage investment in either of the markets cannot currently be justified primarily by financial returns but needs strategic support.

KEYWORDS: battery energy storage, frequency control markets, investment potential

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TIIVISTELMÄ:

Energian varastoinnin tarve tulevaisuuden voimajärjestelmissä on tunnustettu sekä kirjallisuudessa että teollisuudessa. Samanaikaisesti akkuteknologiat, erityisesti Litium-ioniakut, ovat kehittyneet kaupallistettaviksi energiavarastoiksi, joilla on lisäksi suotuisa kustannuskehitys. Taajuudensäätömarkkinat taas tarjoavat akuille teknisesti ja kaupallisesti hyödynnettävät puitteet tarjoten investointimahdollisuuksia. Euroopassa akkuinvestointien johtavat markkinat ovat Saksassa ja Britanniassa, mutta investointien kaupallinen toteuttamiskelpoisuus näihin maihin on kuitenkin säilynyt epäselvänä.

Tämän tutkimuksen tarkoitus oli tarjota kokonaisvaltainen ja vertaileva markkina-analyysi ja demonstroida mahdollisia akkuinvestointikannattavuuksia Saksassa ja Britanniassa. Tutkimus pyrki lisäksi osoittamaan rajaehdot toivotun kannattavuuden saavuttamiseksi. Tutkimus tarkasteli ja analysoi investointipotentiaalia useista näkökulmista taajuuden primäärisäätömarkkinoilla Saksassa ja tehostetun vastereaktion markkinoilla Britanniassa. Maat myös vertailtiin keskenään analyyttisellä hierarkia prosessilla. Lopulta tehtiin taloudelliset simulaatiot Monte Carlo -menetelmällä tulo- ja kustannusepävarmuudet huomioiden. Simulaatioita käytettiin myös vaadittujen kannattavuusrajaehtojen löytämiseksi. Analysoitu data perustui historialliseen markkinadataan, toteutettuun markkinatutkimukseen ja alan kirjallisuuteen.

Tärkeimmät tulokset paljastivat, että valitut markkinat muodostavan sopivan kaupallisen perustan akkuinvestoinneille. Maiden joukosta Saksa kuitenkin osoittautui huomattavasti potentiaalisemmaksi. Toisaalta potentiaalit olivat myös kyseenalaistettavissa, sillä molemmilla markkinoilla osoittautua olevan merkittäviä taloudellisia haasteita. Nämä haasteet myös vahvistuivat simulaatioilla, jotka osoittivat Saksassa noin 1–5 % ja Britanniassa noin -3–3 % sisäisiä korkokantoja investoinneille. Lisäksi 6 % tavoitteen saavuttaminen nähtiin hyvin haasteellisena, kun taas yli 10 % korkokannan saavuttamien nähtiin epärealistisena Britanniassa ja erityisen optimistisena Saksassa. Lopullinen johtopäätelmä oli, että akkuinvestoinnit valituilla markkinoilla eivät tällä hetkellä ole perusteltavissa ensisijaisesti investointituotoilla, vaan ne vaativat lisäksi strategisen tuen.

AVAINSANAT: akkuenergiavarasto, taajuudensäätömarkkinat, investointipotentiaali

1 INTRODUCTION

Energy systems are undergoing fundamental changes. The changes will reshape the systems and revolutionize how we generate, distribute and use energy. One of the most considerable change is increasing role of renewable energy in power generation. Indeed, the electricity generation portfolios are changing rapidly around the world due to emission reduction pressures (Luo, Wang, Dooner & Clarke 2015: 511). To meet the emission reduction targets, electricity generation will develop towards diminishing reliance on fossil fuels with growing role of renewable energy sources (Luo, Wang et al. 2015: 511).

However, renewables come with challenges. High share of fluctuating renewable energy generation increases intermittency of electricity supply disrupting grid stability (Zakeri & Syri 2015: 570). Hence, power systems are facing major challenges in terms of transmission and distribution in meeting demand with stochastic variation (Luo, Wang et al. 2015: 511). Grid scale energy storing is regarded as a promising way to offset the challenges to ensure reliable power supply. Traditionally energy storages (ESs) have been proposed to perform such large-scale energy management by shifting energy over time periods. However, several studies, most recently Zafirakis, Chalvatzis, Baiocchi and Daskalakis (2016), have confirmed unprofitability of such business model. In addition, matching supply and demand is required also in short term in terms of frequency control.

Among ES technologies battery energy storage systems (BESSs) are technically suitable for frequency control services and have attractive cost development. Indeed, BESSs are considered as promising technologies for frequency control (Pan, Xu, Song & Lu 2015: 1139). In addition, frequency control services generally show high value among ancillary services in various market studies (Fitzgerald, Mandel, Morris & Touati 2015: 5). As such, frequency control markets have been natural and in many cases the only commercially applicable business for BESSs. In fact, this business model has been dominating European ES investments in recent years, whilst Germany and the UK have been receiving majority of industrial investments. However, commercial BESS investment potential and financial performance in the countries has remained unclear.

1.1 Literature review

Increasing market potential and academic, industrial and political interests are raising practical energy storage research need. However, in literature economic ES performance has been focused on individual technology performance and business models related to large scale renewables balancing via energy arbitrage. While Zakeri and Syri (2015) discuss variety of technologies in terms of life cycle costs, Pawel (2014) discusses levelized cost of stored energy in more technology neutral manner. Meanwhile, financial performance and favorable cost and market conditions in energy arbitrage has been explored for instance by Bradbury, Pratson and Patiño-Echeverri (2014) for US and by Zafirakis et al. (2016) for Europe. In addition, a range of purely technological studies have been carried out by providing overview of current technology developments by Luo, Wang et al. (2015), Gallo, Simões-Moreira, Costa, Santos and Moutinho dos Santos (2016) and Zhao, Wu, Hu, Xu and Rasmussen (2015).

Literature concerning BESS in frequency control is somewhat limited but recognized. In fact, Aditya and Das (2001) showed already in 2001 the technical viability of BESS in frequency control. Technical aspects have indeed been in focus also in BESSs research. Especially optimal battery sizing together with control logic aspects have been explored for instance by Aghamohammadi and Abdolahinia (2014), Zhang (2016) and Lian, Sims, Yu, Wang and Dunn (2017). Swierczynski, Stroe, Stan and Teodorescu (2013) have also shown, with a case in Denmark, that frequency control with BESS can be profitable. Potential profitability for the UK market was very recently supported also by Lian et al. (2017). However, neither of the studies take into account holistic business environment analysis or related uncertainty factors.

As such, the research of ESs has been active with wide topic spread. However, valid research information is missing especially when evaluating current investment potential in terms of business environment and financial performance under market uncertainties in frequency control markets in the UK and Germany. The lack of research in financial performance of energy storages in balancing services in general has been pointed out also earlier by Ferreira, Garde, Fulli, Kling and Lopes (2013).

1.2 Scope of the thesis

The scope of the thesis covers country specific and comparative primary frequency control market analysis and respective BESS investment analysis under uncertain market conditions. Purpose of the study is to evaluate and compare BESS investment potential in Germany and the UK with simulated financial performances. The study utilizes multimethod approach while main methods are online market research, Analytical Hierarchy Process and Monte Carlo simulation. The methods aim to comprehensively answer the three research questions:

Concerning battery energy storage investments in primary frequency control markets in Germany and the United Kingdom: 1) are the markets attractive, 2) which market involves the highest investment potential and 3) what are the financial performances for grid scale investments in the chosen markets?

1.3 Structure of the thesis

The structure of the thesis follows problem arrangement and the chosen methodology. The introduction is followed by chapter that forms the background on frequency control and defines the target markets. The third chapter discusses technology characteristics and limitations together with recognized business models further justifying the position of BESSs in ES sector. These literature and background chapters are then followed by a chapter explaining the research methodology in greater detail.

The fifth chapter answers the first and the second part of the research question. It explores and compares the markets in depth by showing the results of online market research and market comparison with analytical hierarchy process. The sixth chapter then focuses on quantitative analysis by showing the results of investment analysis based on market operation simulations with Monte Carlo method. The last chapter concludes the study with further discussion and summary.

2 ELECTRICITY AND FREQUENCY CONTROL MARKETS

Electricity as a commodity is traded in power exchanges in liberalized power markets. However, due to the nature of the product, electricity trading, markets and related energy deliveries involve several support activities in order to secure reliable and safe power system. Frequency controlling is part of these support activities whilst corresponding markets are established to perform the services efficiently and in economic manner.

2.1 Electricity market structure

Electricity markets are always tied to certain geographical area, region or country where power consumption takes place. In Europe, these price areas are highly interrelated due to integrated internal markets with good interconnection capabilities. Hence, the overall electricity markets within European Union are relatively similar and can be generally divided in three main parts: financial, physical and settlement. The parts are complementary, and operated for very different purposes.

Financial market comprises from future and forward contracts. The contracts are commitments between the buyer and the seller and they determine the price at which the two parties are willing to trade power in certain area at a predetermined future moment. However, usually these contracts do not involve physical power delivery, but the payments between the price determined in the contract and realized wholesale price is settled and paid between the parties. Hence, the price difference payments guarantee the price level the seller receives for selling and the buyer pays for buying actual electricity later from physical markets. As such, the contracts are issued for hedging purposes in order to mitigate risks related to electricity wholesale price development. Forwards and futures are traded in long to medium term – usually a few years ahead.

Physical markets are the actual power markets where the energy is traded, delivered and balanced with consumption. Physical market may be further divided in day-ahead spot market, intraday market and balancing and ancillary service markets. Spot market is the main wholesale market where majority of the electricity is traded in most liberalized markets. Spot markets are run as closed bid reverse auctions for deliveries during next day with hourly resolution. The time gap between trading and delivery allows market participants to adjust their generation and consumption schedules based on the auction results. Whereas, intraday energy markets are more real time and allow market participants to trade energy for coming hours within current (and next) day. Intraday market enables additional power trading and market based reactions for generation and consumption balancing need both on a system level and internally for market operators. However, in order to secure the power system operations, balancing and ancillary service markets are needed. They are further discussed in section 2.3 and 2.4.

Settlement part includes settling all the prevailing contracts and payment obligations. Settlements are made after the deliveries or contract maturities. However, due to continuous nature and high frequency of transactions, the settlements are made usually within days after the closings. General structure of electricity markets is illustrated in figure 1.

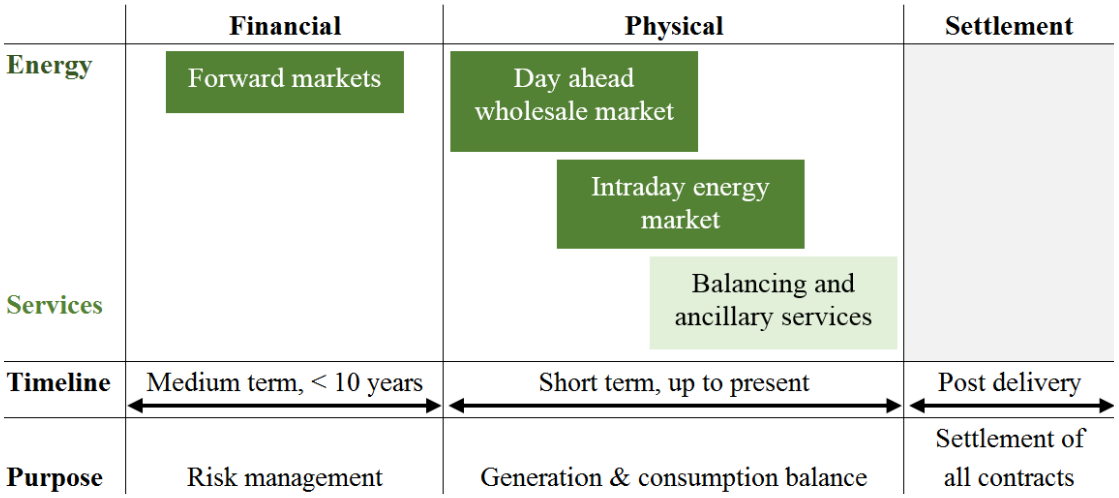
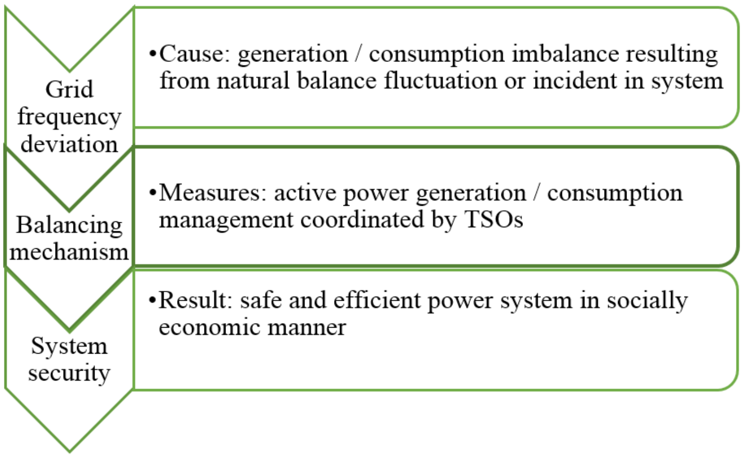


Figure 1. General structure and main components of free electricity markets. Over the counter financial and physical markets also exist in most countries.

2.2 Balancing mechanism

Electricity in any power system must be generated and consumed at the same time (ENTSO-E 2017b: 2). However, generation and consumption are naturally varying in real time despite day-ahead and intraday contracts. This imbalance may result from changes in numerous generation and consumption units, incidents or other grid disturbing events. The imbalance must be offset by adjusting power supply and demand accordingly. This balancing process is defined as balancing mechanism.

Imbalance between real time generation and consumption causes frequency deviations from grid nominal value in alternative current power systems. Too large system frequency deviations may lead e.g. to disconnection of generators and thus endangers the system security (Pirbazari 2010: 33). The deviation is managed within issued control limits by actively controlling system level power output (or consumption) (Pirbazari 2010: 33). This is performed by transmission network operators (TSOs) who control the power balance by utilizing measures based on the established balancing mechanism and available balancing generation/consumption assets. Balancing mechanism and frequency control markets are set to overcome related problems and provide required assets for TSO's use in economic manner. Usually it is achieved by implementing a market mechanism for the required services. The role of the mechanism is illustrated in figure 2.



- Cause: generation / consumption imbalance resulting from natural balance fluctuation or incident in system
- Measures: active power generation / consumption management coordinated by TSOs
- Result: safe and efficient power system in socially economic manner

Figure 2. The role of balancing mechanism in power system security.

Frequency control services themselves are part of the balancing mechanism and belong also to a larger group of ancillary services (AS). Frequency control services here are defined as short term balancing services responding to balancing need within few hours. Whereas, AS include several individual and interrelated services and are defined as services procured by TSOs to maintain power balance, stabilizing the transmission system and to maintain power quality (Pirbazari 2010: 32). However, country specific market elements and operating arrangements differ widely. As such, the definition of AS is not unambiguous. For instance, Pirbazari (2010: 33) elaborates AS in competitive power markets to include frequency control, voltage control, spinning reserves, standing reserve, black start capability and emergency control actions. All in all, they refer to a group of functions TSOs contract in order to ensure system security (ENTSO-E 2017a). Since frequency control services show the highest value and BESS business potential among ancillary services (Fitzgerald, et al. 2015: 5), the study will focus on them from this point forward.

2.2.1 Frequency control principles

Frequency controlling is purely driven by a system need i.e. a frequency deviation resulting from power surplus or deficit. Power surplus results in high frequency, which leads to down control by decreasing power generation or increasing demand. The situation is opposite in a power deficit situation with low frequency. High and low frequencies are defined respectively as values above and below the grid nominal value, which is 50,00 Hz in both studied countries. However, frequency control reserves are usually not activated right after frequency deviation, but after defined threshold called deadband. Deadband is illustrated in figure 3 as frequency range between the inner dotted lines. Deadband may vary for different units based on their reaction speed, but minimum requirements are set by TSOs. However, unit specific parameters should be set so that the service providing unit can reach 100 % power of committed capacity at latest in predefined frequency limit. These cap limits are illustrated by outer dotted lines in figure 3. Between the deadband and maximum limits, controlling power activation amount is determined linearly in dynamic services. In static services the activated amount is fixed.

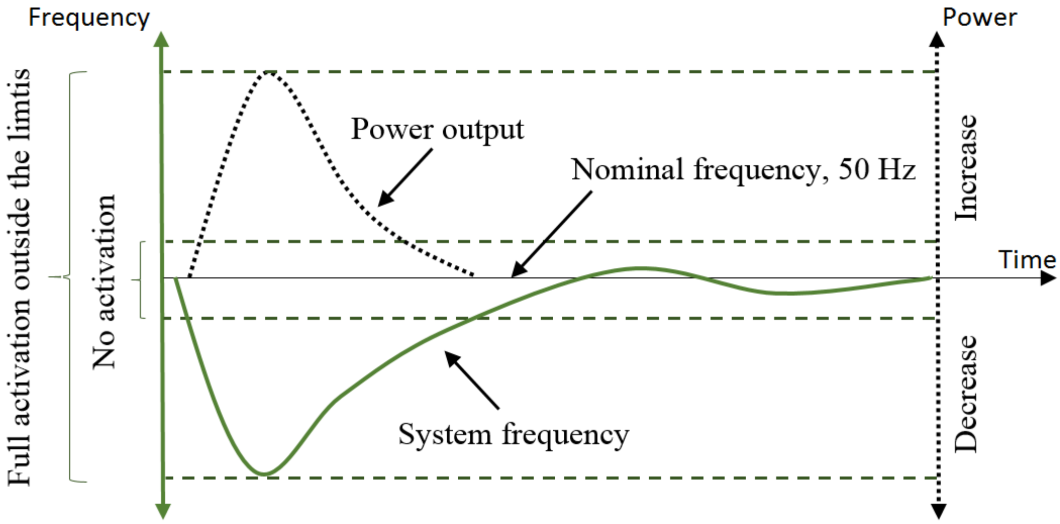


Figure 3. Frequency control principle with frequency deviation and respective power output change in power deficit situation.

Frequency control system and process itself is generally divided in primary, secondary and tertiary levels (Pirbazari 2010: 33). The levels may further be divided in different service products procured by the TSOs. However, the main principle is that the three levels are both substitutive and complementary, activated at different time spans and thus enabling the system to react fast while keeping the readiness to react to a new shock every time. Frequency control service levels in general are illustrated in figure 4 below. The illustration and elaborations below are based on central Europe system, but are generalizable in most power systems.

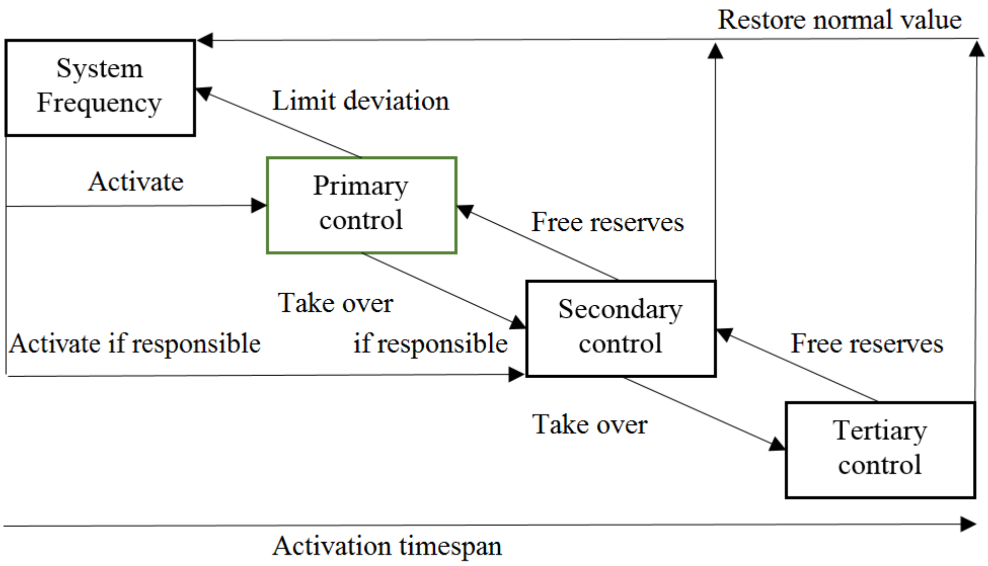


Figure 4. Frequency control service levels with interrelations and purposes (based on ENTSO-E 2009: 2).

Primary control aims to maintain the power system balance within the synchronous frequency area collectively in cooperation of all TSOs and reserves within the control area. It is activated within seconds after frequency deviation shock (disturbance, imbalance or incident), but it is not meant to restore the frequency over a long period. (ENTSO-E 2009: 4.) Primary control reserves are automatically activated by system frequency within the set control limits. Primary controlling is a continuous operation and as such control power must be available for delivery until the power need is completely replaced by secondary and tertiary control reserves (ENTSO-E 2009: 7).

If the control need continues, secondary reserves are activated usually automatically by TSOs based on the frequency and set to replace and free the primary ones within minutes (ENTSO-E 2009: 2). Secondary control reserves aim to maintain the balance within each control area within the synchronous area and they are operated in a timespan from seconds normally up to 15 minutes from frequency deviation incident (ENTSO-E 2009: 12).

Finally, tertiary control reserves refer to changes and re-scheduling in power generation or demand which may be contractual, regulatory or market based. Tertiary control reserves are control area specific and usually manually activated by TSOs in case of expected continuing activation of secondary control reserves. Tertiary reserves are primarily activated to free secondary reserves in order to restore the system frequency, but they may be used also to complement secondary reserves in a case of major incident. Activation timespans for the levels are illustrated in figure 5 for low frequency shock.

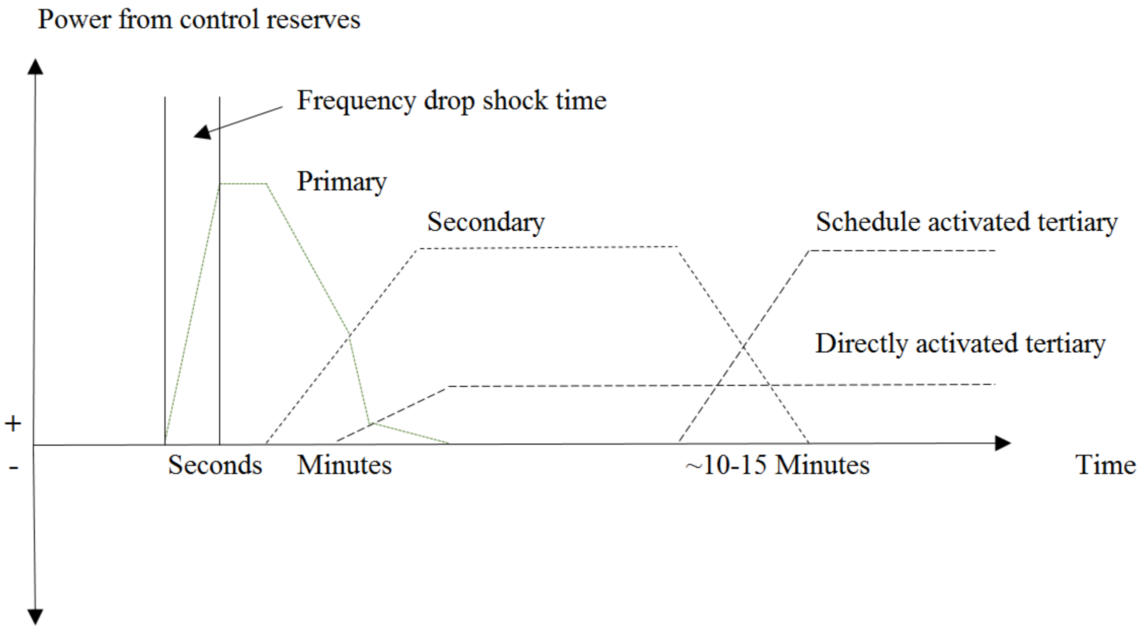


Figure 5. Frequency control reserve activation principle in timeline in case of sudden power deficit (based on ENTSO-E 2009).

2.2.2 Frequency control areas

European power system consists of five larger sub-systems, regional groups, which are individually operated in European cooperation. These regional areas have synchronous system frequency and thus are also controlled in firm cooperation. The synchronous areas put together 5 permanent regional groups of the System Operations Committee of European Network of Transmission System Operators for Electricity (ENTSO-E). The regional groups (continental Europe, Nordic, Baltic, United Kingdom and Ireland) are to ensure integrity between system operations, market solutions and system development.

The regional groups are further divided to control areas, which are defined as “a coherent part of the interconnected system, operated by a single system operator (TSO) and shall include connected physical loads and/or generation units if any” (European Commission 2013: 543/2013, Article 2(6)). Each TSO and respective control area is responsible in implementing and operating in terms defined in frequency control structure of its area (ENTSO-E 2013). However, within the defined framework TSOs have a freedom to choose how to fulfill the responsibilities in terms of frequency control service definitions and markets. This way also the related frequency control markets between and within the regional groups are different providing various operating schemes for energy storages.

2.3 Frequency control market – Germany

Germany has a central role and location in continental Europe power system. Within Continental Europe regional group Germany itself comprises from four control areas operated by four individual TSOs: 50Hertz (east), TenneT (north – south), Amprion (west), TransnetBW (south – west). Each TSO is responsible for sufficient frequency control reserve provision. Nevertheless, the TSOs are operating and procuring control services based on national principles within the continental Europe framework.

2.3.1 Market structure

German system is based on competitive market. The TSOs answer their control reserve need by procuring the capacity via shared online platform *Regelleingstun.net* (Regelleingstun.net 2017a). The TSOs announce shared tendering calls, and prequalified service providers deliver their bids for closed bid reverse auction in the market platform for all control services. Anonymous auction results are then published, accepted bids committed for tendered period and payments paid as bid. The market structure is illustrated in figure 6.

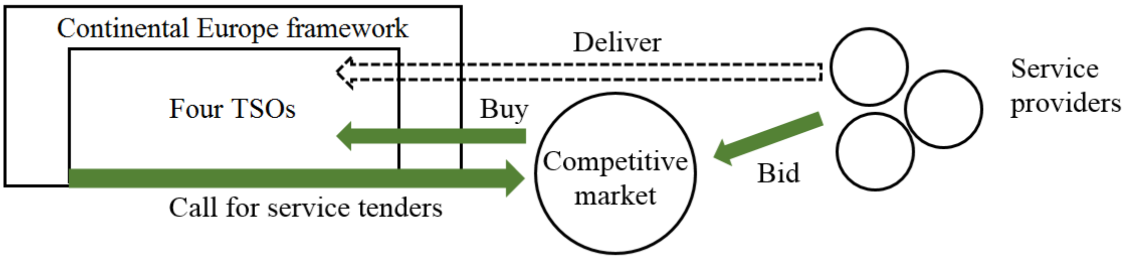


Figure 6. German market structure for frequency control services. In Germany competitive market is operated in online platform. Dotted arrow illustrates service delivery whereas green arrows market operations.

System itself includes three control layers, which form three service products for frequency control market. These services are primary, secondary and minute reserves and they follow directly the principles introduced earlier in section 2.2.1. The service products are reserved capacity, thus the service provider reserves accepted capacity for TSO's use. Depending on the service, TSO pays only for the capacity or both reserved capacity and delivered energy. Service details are elaborated in table 1.

Table 1. Summary of German frequency control service products (Regelleistung.net 2017b, Belhomme, Trotignon, Cantenot, Dallagi, Cerqueira, Hoffmann, Burger & Eberbach 2015: 5, Consentec 2012: 13–15, Hollinger, Diazgranados & Erge. 2015: 1).

	Primary	**Secondary**	**Minute**
Commitment period	1 Week	1 Week	1 Day
Capacity limits	1 - 150 MW	Min 5 MW	Min 5 MW
Control direction	Symmetrical ±	+ and - separately	+ and - separately
Activation	Automatic	Automatic	Manual
Activation start	30 s	5 Min	Varies
Max activation	< 15 Min	< 15 Min	Hours
Response in frequency	Dynamic	Dynamic	Static
Payment logic	Pay-as-bid	Pay-as-bid	Pay-as-bid
Payment based on	Capacity	Capacity + energy	Capacity + energy

From BESS point of view the service characteristics limit business opportunities significantly. Firstly, BESSs have limited energy capacity, which means they cannot provide power increase or decrease for long periods. This fact narrows minute reserve market out as the duration can be several hours – answering the requirements would result in very high investment costs without respective reimbursement potential. In addition, up and down control services are bid and operated separately for secondary and minute reserve market. This is a problematic issue and narrows also secondary control out as participating in unidirectional service would increase unavailability risk due to limited energy capacity. In contrast, expectation value for charged and discharged energy in symmetrical service is zero. Furthermore, faster responding services are activated more frequently and as such have higher value in system sense. Thus, they also have higher revenue potential and make primary control reserve (PCR) market the most attractive and applicable for BESSs in Germany. PCR market has also been the primary target market for BESSs investors to this day and hence will be also in the focus of this study.

2.3.2 Primary control reserve market characteristics

German PCR auctions, operated in Regelleingstun.net, apply pay-as-bid principle (Hollinger et al. 2015: 5). PCR providers are paid only for capacity (€/MW) and not for delivered energy as in the case of secondary and minute reserves (Hollinger, et al. 2015: 1). Pay-as-bid markets allow applying different bidding strategies which in such a system have a critical role in profit making (Hollinger et al. 2015: 5). Indeed, the system gives an initiative to bid higher prices as in uniform price systems (Hollinger et al. 2015: 5). In pay as bid system, the lowest costs do not always yield in the highest margins as assets with higher costs may reach even higher prices.

Auctions are held weekly (every Tuesday) for a period of one week from Monday to Sunday (Consentec 2012: 13; Regelleistung.net 2017c). The commitment period is always a whole week with 100 % availability requirement (Consentec 2012: 13; Hollinger et al. 2015: 1). Availability can be ensured via pooling the units i.e. including several units to form a controllable entity. Pooling units are allowed within one control area, unit assignment to a pool can be changed within the commitment period and units actually providing PCR may vary at any time within a pool (Consentec 2012: 13-14).

Control direction between positive and negative is not separated in tenders calls and bidding suppliers are expected to be able for symmetrical power deliveries in both directions. However, unidirectional units (i.e. units capable only to increase or decrease power output) can be pooled to fulfill the symmetry requirement (Consentec 2012: 14).

PCR bids are currently restricted by volume to 1–150 MW (Regelleigstung.net 2017d, Hollinger et al. 2015: 1). Bidding volume can be increased with steps of 1 MW (Consentec 2012: 14). Full activation of the bid capacity must be reached within 30 seconds from the frequency shock (Hollinger, et al. 2015: 1). The primary control reserves must be capable for at least 15 minutes of power delivery (ENTSO-E 2009: 7).

Bidding in German PCR markets actually includes bidding in several markets: PCR tenders are joint tenders for German, Belgian, Dutch, French, Swiss and Austrian markets. Qualified suppliers are thus bidding for cross-border trades at several countries. However, despite international tendering, maximum amount for PCR export in joint tenderings is set to 30 % of the country’s total PCR need, but no less than 90 MW. France joined the joint market in 2017 and it currently has stricter import-export limitations. The country will currently export 84 MW and import 169 MW of PCR at maximum. The rest, including Germany, do not face import limitations. (Regelleigstung.net 2017b.)

2.4 Frequency control market – the UK

The UK belongs to a separate regional group comprising from three TSOs: National Grid Electricity Transmission plc, Scottish and Southern Energy plc and Scottish Power Transmission plc (ENTSO-E 2015c). However, system level operational responsibility in the UK is solely assigned to National Grid (Ofgem 2017a).

The UK operates the power system currently based on European network codes that are European law, and takes priority in case of conflict with national legislation (National Grid 2017a). Although the basic system operation guidelines follow the ones in continental Europe, the balancing procedures and framework vary greatly with different set of frequency control services.

2.4.1 Market structure

The market structure in the UK is bipartite with parallel competitive market and mandatory service provision. Frequency response service provision (i.e. control services) is mandatory for all large generators with at least 100 MW capacity and generators that are connected to the UK's transmission network (National Grid 2017f). Competitive market for frequency response services is run by National Grid through tenderings and is open for units that are not part of mandatory provision. The market is a closed bid reverse auction with paid-as-bid reimbursements. The results are published afterwards and the winning units committed for the services. Market structure is illustrated in figure 7.

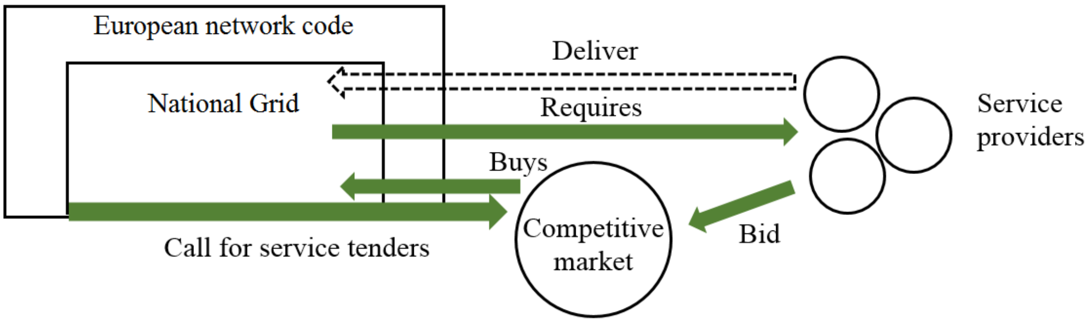


Figure 7. Structure for frequency response services markets in the UK. Both the competitive market and the mandatory service provision exists. Dotted arrow illustrates service delivery whereas green arrows operations by the TSO and service providers.

The market based balancing service portfolio in the UK is much wider in comparison with Germany. The services can be divided in two main categories: response and reserve services. Response services are for fast and short term frequency controlling and can be seen covering the primary and secondary levels in general balancing structure. Whilst, reserve products cover longer balancing need on tertiary level. The commercial response services include enhanced, primary, secondary and high frequency responses, whereas reserve products are divided in fast, negative and other reserve products (National grid 2016a). Primary, secondary and high responses are also mandatory for large generators. In addition, separate markets for demand side management exists. Features and technical requirements for frequency response services are summarized in table 2.

Table 2. Characteristics and technical minimum requirements for commercial frequency response services in the UK (National Grid 2017b; National Grid 2016f: 10–19).

	Enhanced	**Primary**	**Secondary**	**High**
Commitment period	4 years	Min 1 hour	Min 1 hour	Min 1 hour
Capacity limits (MW)	1–50	Min 10	Min 10 MW	Min 10 MW
Control direction	±	+	+	-
Activation	Automatic	Automatic	Automatic	Automatic
Activation start	1 s	10 s	30 s	10 s
Max activation	15 min	20 s	30 min	indefinite
Response in frequency	dynamic	static/dynamic	static/dynamic	static/dynamic
Payment logic	Pay-as-bid	Pay-as-bid	Pay-as-bid	Pay-as-bid
Payment based on	Capacity	Capacity + energy	Capacity + energy	Capacity + energy

The UK's response services are automatically activated within seconds by the frequency, whereas reserve services are manually activated within minutes by the TSO (National Grid 2016a). The activation logic is similar to continental Europe: faster responding units are taken over by the next level services as time goes by and if the control need continues. However, unidirectional approach makes the market differ substantially from the market of Germany: there are different balancing services for up and downward controlling and only one symmetrical frequency control service. Response and reserve services with control direction and typical activation time spans are illustrated in figure 8 below.

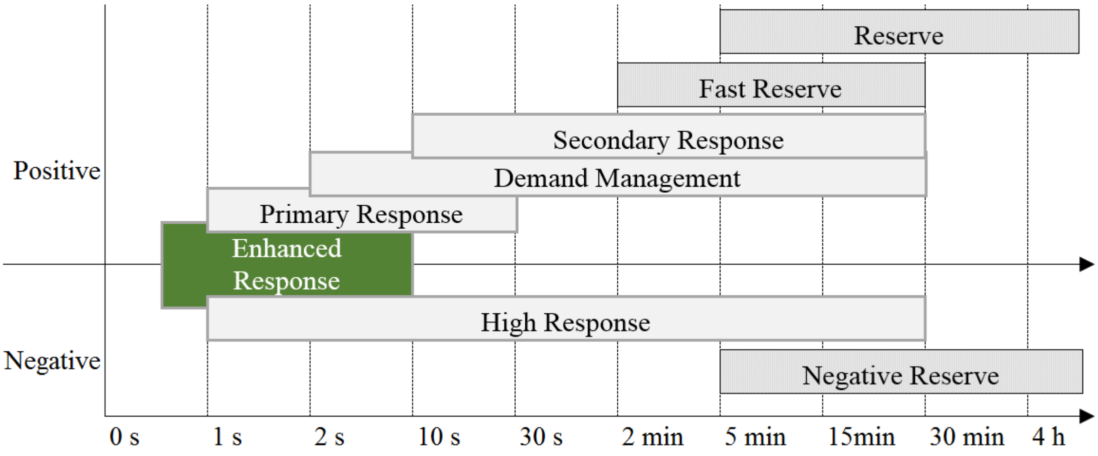


Figure 8. Balancing and frequency control services in the UK with typical activation time span and control direction (based on National Grid 2016a).

Limited energy capacity of BESS limits the possibility to offer reserve services with long duration in the UK. In addition, unidirectional services are less potential for standalone BESS as discussed earlier. This is a major disadvantage and limits primary, secondary and high response services provision of BESS. For instance, monthly energy imbalance between control directions during 12/2016–2/2017 averaged in over 400 000 MWh nationally. The imbalance is illustrated in figure 9. Furthermore, as high response may be continued indefinitely, performance of standalone BESS becomes a major concern. Hence, enhanced frequency response (EFR) is considered to be the primary market for BESS in the UK within balancing mechanism. This is also the case for large scale BESSs currently available or under construction.

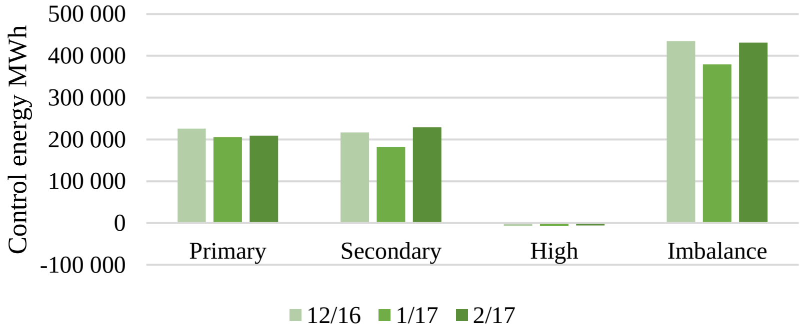


Figure 9. Monthly energy volumes and total directional imbalance between the UK's unidirectional frequency response services (data: National Grid 2017e).

2.4.2 Enhanced frequency response market characteristics

The first closed bid reverse auction tender for EFR was in 2016. The first units providing EFR are expected to start operating during 2017 (National Grid 2016d). EFR is both complementary and replacing service for the UK’s traditional frequency response services. However, it should be emphasized that the TSO has not published market characteristics after the first contracts expire. Thus, the study here is based on 2016 tender and announced future anticipations.

The TSO procured 200 MW of service capacity in initial tender (National Grid 2017d). The accepted bids were contracted with four-year contracts starting in winter 2017/18 (National Grid 2017d). However, the TSO expects the need for EFR to grow, and is thus expecting regular auctions in the future (National Grid 2016f: 14). In 2016 auction the TSO held capacity range 1–50 MW for a single provider to prevent concentration. However, the limit is likely removed in the future (National Grid 2016f: 10).

Capacity based pay-as bid payments are corrected with unavailability costs resulting from service delivery below required 95 % availability level (National Grid 2016f: 21). However, aggregating demand and generation assets is accepted in order to increase availability and reach sufficient capacity (National Grid 2016f: 9 –11). Payments are made based on performance during each half-hour settlement period. The performance is measured by comparing normalized response power against given envelope second by second. This gives the percentage rate at which the unit was able to operate noticing the service need. The envelope is a target fluctuation limit based on the frequency value (i.e. what should have been delivered), whilst normalized response means the percentage value of actual response from the operational reported capacity (i.e what was actually delivered). Second by second performance values are averaged to half-hourly values giving service performance measure. The service performance measure is then turned to an availability factor based on the table 3 below. Finally, total payment for each half-hour is calculated as in equation 1. In addition, annual performance average is calculated and should not be less than the 95 % limit. (National Grid 2016f: 5–6.)

Table 3. Availability factor determination from performance measure (National Grid 2016f: 6).

Service Performance Measure	**Availability Factor**
< 10 %	0 %
> 10 %, < 60 %	50 %
> 60 %, < 95 %	75 %
> 95 %	100 %

$$EFR\ payment = power\ capacity \times ½\ hour\ price \times availability\ factor \qquad (1).$$

3 ENERGY STORAGES

Energy storages are devices capable of storing energy in any form. However, ES in the scope of this study means grid connected electrical energy storage. Electrical energy storages are defined as devices capable of absorbing electrical energy, storing energy in any form and delivering the stored energy back in electrical form. Whereas, grid connection in the context means possibility to utilize transmission grid for charging and discharging. The principal of electrical energy storage is illustrated in figure 10.

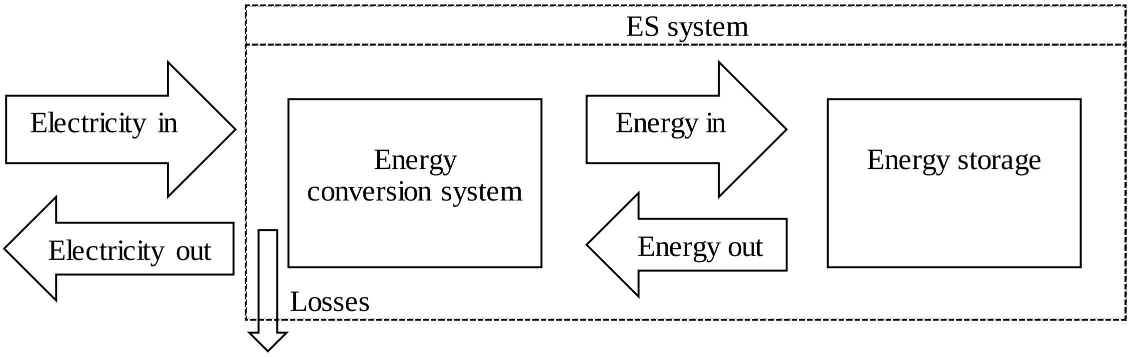


Figure 10. High level principal picture of electrical energy storage.

There are several available ES technologies and their technical characteristics have been widely discussed in literature (e.g. Mahlia, Saktisahdan, Jannifar, Hasan & Matseelar 2014; Cho, Jeong & Kim 2015; Pearre & Swan 2015). In addition, possible revenue streams and business models come with variety. Since the technologies are already widely discussed, this chapter will cover the topic only briefly by main features with the focus on battery energy storages. Technology part is then followed by introduction to potential revenue streams for utility scale ES.

3.1 Battery energy storage system

BESS is a technology group that covers several technologies, which all store energy in a chemical form. Conventional batteries are a sub group that comprise low-voltage battery cells, which are connected in series or parallel in order to reach desirable electrical features (Zhao et al. 2015: 547–548). Electrical energy is converted to chemical form within the cells via electrochemical reactions. Respectively these reactions are run reversibly during discharge when the energy is converted back to electric current. Commonly recognized technology variations for commercial applications include lead acid, Nickel Cadmium, Nickel Metal Hybrid, Lithium ion (Li-ion) and Sodium Sulphur batteries (Zhao et al. 2015: 548). Such conventional BESS technologies all follow the general principle from figure 10, whilst the main differences regard electrochemical materials and reactions concerning the storing process.

The benefits of BESSs are rapid response times (< second), small self-discharge losses, high round-trip energy efficiency and large energy and power densities (Zhao et al. 2015: 548). In addition, the technologies are widely demonstrated and used while many are also projected to face significant cost reductions in the future. On the other hand, batteries come with relatively limited lifetime, high capital costs, and most of the technologies include hazardous materials (Zhao et al. 2015: 548). Nevertheless, BESS technologies, especially Li-ion, has faced significant development in recent years from both technical and commercial perspectives. The development and increasing deployment are driven especially by sharp increase in demand and fall in capital costs. Whereas, these trends are driven especially by fast growing electric vehicle market. Such positive twist is self-stimulating and has assisted Li-ion to take a dominant role also in new BESS investments in power industry (data: Sandia National Laboratories 2017).

3.1.1 Li-ion battery energy storage technology

Since the dominant role of Li-ion in BESS investments is the case also in Germany and the UK, this study will use the technology as a benchmark and basis for analysis and calculations. There is a range of technical research available also within Li-ion technology itself and the characteristics shown here are represented in general level. Nevertheless, quantified values for power and energy capacities, roundtrip efficiency and for lifetimes in years and in cycles are summarized in table 4.

Table 4. Summary of key features for Li-ion BESS technology. Power and energy capacities are typical values since the technology is scalable beyond the indicated values. (Data: Zhao et al. 2015: 547; Zakeri & Syri 2015: 592.)

	Power capacity	**Energy capacity**	**Efficiency**	**Lifetime**	**Life cycles**
Li-ion BESS	0.1 – 50 MW	0.1 – 100 MWh	85–95 %	5–15 years	2000–5000

In practice, power and energy capacities have a wide range while many R&D and demonstration units have realized with maximum of 5 MW and 5 MWh, whilst larger commercial installations have reached 50–100 MW and 50–150 MWh capacities. Even larger several hundred MW and MWh units have been installed globally. As such, Li-ion BESS provides great scalability, which has supported its commercialization. It has been supported also by the energy efficiency of 85–95 %, which yields in small variable costs. Small variable costs are actually vital in order to increase financial performance since lifetime of only 5–15 years requires large marginal in such capital-intensive investment. Lifetime in cycles means how many computational charging and discharging cycles the batteries last and is around 2000–5000 for Li-ion. Consequently, if BESS is applied in low intensity operations, the lifetime in years may increase above the indicated lifetime in years.

Li-ion technology itself is regarded as reliable, but limited energy capacity restricts charging and discharging in case of high and low state of charge respectively. Thus, the battery is required to maintain its state of charge, resulting in potential unavailability and respective costs. For instance, German frequency data from 2011 shows that continuous one directional frequency control activation was required for up to 140 minutes (Consentec 2012: 14). Within such a period it is highly potential that BESS reaches its capacity limits. Moreover, Xu (2014: 4029) has shown, with continental Europe frequency data, that it is possible to reach 90–99 % availability with active controlling.

Naturally the ratio between installed power and energy capacities has a critical role in BESS availability. This ratio indicator is called C -rate and is simply calculated by dividing power capacity by energy capacity. 1C Indicates that the BESS can provide power output at full capacity for 1 hour. 2C indicates output capability of ½ hour and 0,5C 2 hours etc. The applied rate is often a compromise as e.g. primary frequency control services are often paid based on reserved power capacity, but to ensure required service level, sufficient energy capacity is required as well. Common C -rates for operational BESS Germany is 0,67C and 1.0C in the UK (data: Sandia National Laboratories 2017).

3.1.2 Li-ion investment costs

The decreasing price trend for Li-ion BESSs is expected to continue as the technology matures, the competition tightens, and the demand increases due to increasing number of electric vehicles and large scale ES installations. Nevertheless, most of the cost reduction is realized in actual battery cells while the system level investment costs are more multifaceted. In fact, most of the cost components are relatively stable or have only minor reduction possibilities. These cost components are usually divided in three main categories to calculate ES system level total capital requirement: cost of power conversion system (€/kW), cost of storage section (€/kWh) and cost of balance of plant (Zakeri & Syri 2015: 573). These total capital cost factors are elaborated in table 5.

Table 5.General total capital cost elements and factors for electric ES investment cost calculation (based on Zakeri & Syri 2015: 572; Schoenung 2011: 11).

Total capital cost element	**Cost factor**	**Example**
Power conversion system	Interconnections	Transformers
	Power electronics	Inverters
Storage section	Storage facility	Control system
	Storage technology	Battery banks
Balance of plant	Project management	
	Grid connection	
	Construction management	
	Land and access	
	Buildings	
	Logistics	
	Isolation and protective devices	Switches, fuses
	Monitoring and control system	

Zakeri and Syri (2015) represent composed cost analysis from numerous studies and report for both components separately and on a system level. The study shows Li-ion BESS power conversion system costs ranging from around 250 to 600 €/kW, the average being 463 €/kW. In contrast, storage section costs are ranging significantly more between 450 and 1250 €/kWh, whilst the average is 795 €/kWh. Composed total costs average at 1160 €/kW, but the range is very large 750 €/kW–2400 €/kW (Zakeri & Syri 2015: 583).

In the scope of this study, power conversion system costs are assumed to be 450 €/kW, which is in line with prevailing numbers. Since the conversion system cost elements comprise from mature technology, significant cost reductions aren't included in the estimation. However, storage section costs are adjusted with realized cost reduction and estimated to be currently 440 €/kWh. The estimation equivalents to around 25 % annual decrease since 2015 and is strongly supported by the prices of BESS manufacturers and published Li-ion battery cost estimations (e.g. Nykvist & Nilsson 2015: 329–332). Balance of plant costs are estimated to be 120 €/kW. These cost elements result in 1010 €/kW (/kWh) total cost, which is well in line with the composed estimations by Zakeri and Syri (2015: 585), while showing clearly the realized cost reductions also when compared to installed projects with published costs.

3.1.3 Alternative technologies

The wide range of ES technologies comes with different maturity stages, characteristics, functionalities and costs. These issues have a critical impact on desirable business models and determine also competition among the technologies. However, the following technologies have been most recognized, researched and applied in industry:

- Pumped hydro ES
- Compressed air ES
- Hydrogen ES
- BESS
- Flywheels
- Supercapacitors.

Generally ES technologies can be classified based on the form of the stored energy, but they also have very differing characteristics within these categories. Indeed, features such as response time and power and energy capacities, limit functional applications for different technologies. Thus, the technologies can be classified also based on the primary function of the storage. By function Chen, Cong, Yang, Tan, Li & Ding. (2009: 294) divide the technologies in two categories:

1. Technologies with high power capacities combined with relatively small energy storing capacity
2. Technologies with large energy capacity.

The first group is more suitable for power quality services, whereas the latter one is applicable for larger energy management. Prevailing technologies are illustrated in figure 11 with indicative power and energy capacities and stored energy form.

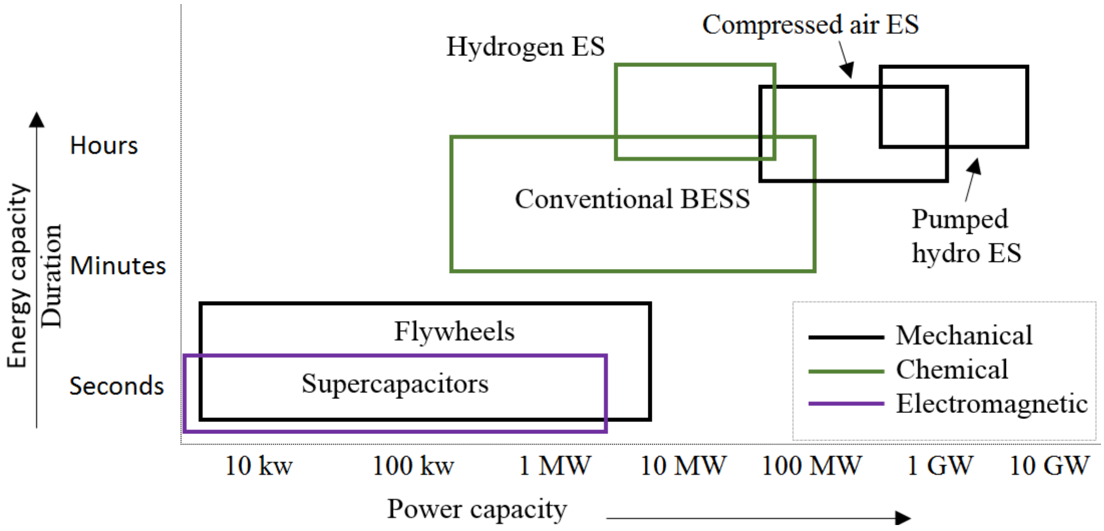


Figure 11. Indicative power and energy capacities for commonly recognized energy storage technology groups. Colors indicate the form of stored energy, whilst energy capacity focus over power capacity increases upwards y -axis. (Data: Zhao et al. 2015: 547; Gallo et al. 2016: 815.)

However, technology relevancy and applicability is also affected by technology maturity stage and related risks. For mentioned technologies, the stages indeed differ greatly while Li-ion BESS has faced the most rapid development in recent years. Maturity stages are illustrated in figure 12. In addition, the total capital cost level and the cost reduction potential are also strongly related to the maturity level. However, technology characteristics set clear boundaries for costs – which are still ranging greatly even within a certain technology. Capital cost ranges for the technologies are illustrated in figure 13.

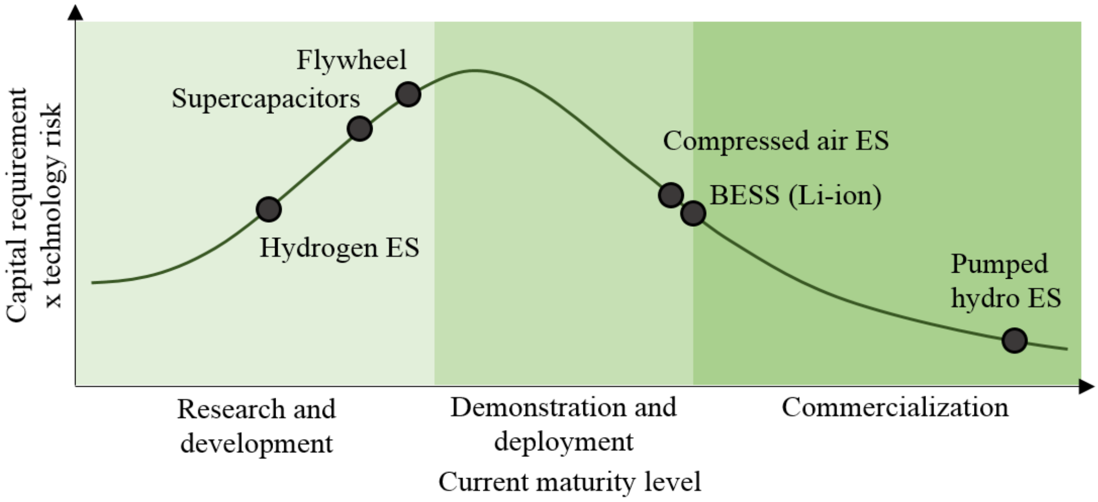


Figure 12.Current maturity stages and product of capital costs and risks for commonly recognized ES technology groups. The stages are based on IEA (2014: 16) and are adjusted with realized development estimations.

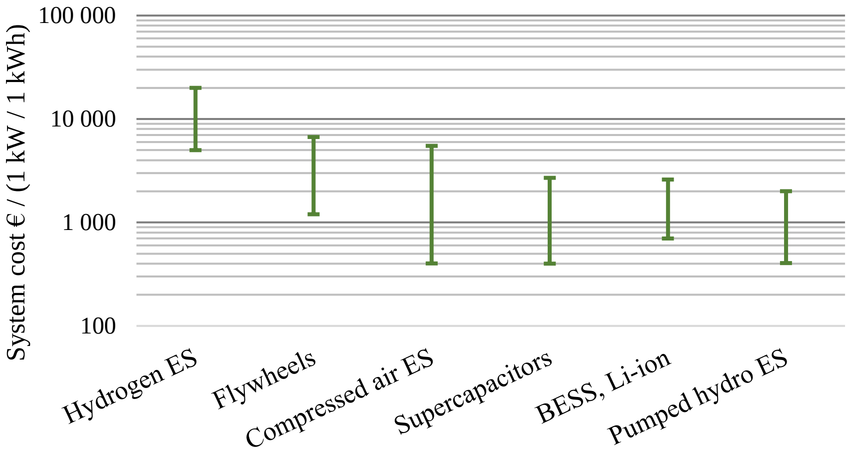


Figure 13. Current total investment costs in logarithmic scale for ESs with 1 C -rate for common ES technology groups (data: Zakeri and Syri 2015: 590–592; Zhao et al. 2015: 547; Gallo et al. 2016: 816).

From frequency control, especially primary level, point of view the technological ES requirements are fast response, high power and moderate energy capacity. Figure 11 illustrates clearly that BESSs meet the energy and power capacity requirements effectively. Maturity level and cost estimations are supporting BESSs as well: commercial state has been reached while only pumped hydro, as the most developed technology, comes with lower upper cap in unit cost range. Compressed air and pumped hydro ESs are clearly more energy focused with also much larger power capacity, which makes them exaggerated for only frequency control purposes. Likewise, this is the case for hydrogen fuel cell systems, but they also face significant disadvantages from maturity, cost and inefficiency (30–50 % roundtrip efficiency) perspectives. The rest reach efficiency range of 70–99% in which BESSs represent the higher end. Furthermore, very limited energy capacity of flywheels and supercapacitors makes them irrelevant since meeting service duration requirements appeals very challenging even though some applications could be cost competitive with BESSs. Hence, increasing BESS penetration and dominance in frequency control applications is technically well justified.

3.2 Energy storage business models

Despite the functional categorization, most of the ES technologies have the necessary flexibility and capability to operate in energy markets by trading energy to gain from arbitrage and by offering services for power quality, reserves and reliability (Staffell & Rustomji 2016: 212). Thus, the potential revenue streams for grid scale ES can be divided in two main categories: arbitrage related and ancillary and other services. These categories include a wide range of business models that further differ among countries due to different market characteristics and regulations. In addition, end consumer based revenue streams are recognized, but are not discussed in this study.

Potential revenue streams for utility scale ESs are illustrated in figure 14 and discussed further below. However, it is important to emphasize that all revenue streams have technical requirements limiting relevant applications. Divya and Østergaard (2009: 517) divide potential ES applications based on their typical activation time and point out that commercially relevant applications for BESS are the ones with short duration and thus focus on power rather than energy. Such services tend to have also higher value in general.

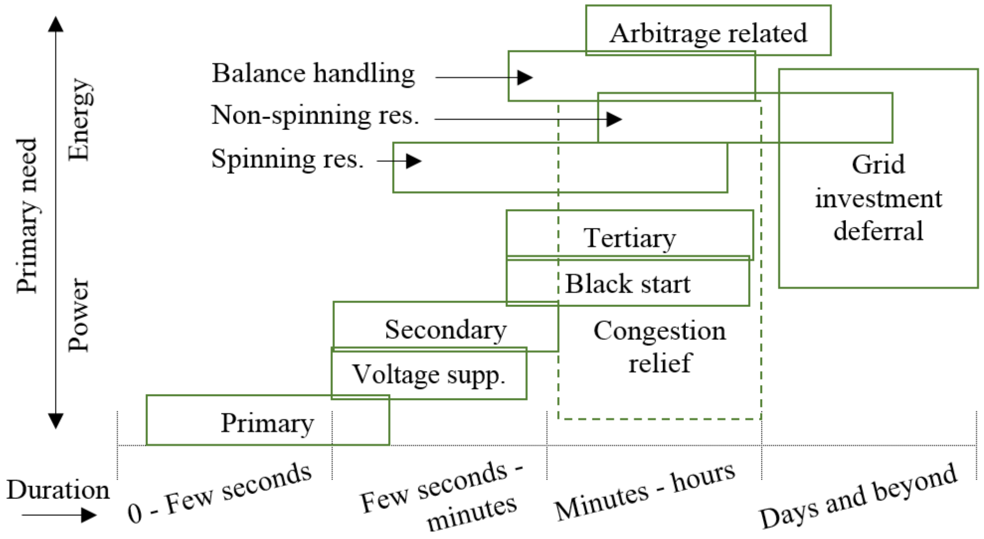


Figure 14. Potential revenue sources for ESs with typical duration and indication whether the business is energy or power focused. Timespan division based is on Divya and Østergaard (2009: 517). Primary, secondary and tertiary refer to frequency control levels.

3.2.1 Ancillary and other services

As pointed out in section 2.2, ancillary service markets and potential revenues are highly dependent on services the TSO and distribution network operator (DNO) in certain area are purchasing. However, flexible ESs and especially BESSs can provide several different services within the category. In addition, business models themselves may include one or more services simultaneously or separately. Relevant utility scale ancillary and other services introduced in figure 14 are summarized in table 6.

Table 6. Summary of utility scale services applicable for ESs. All of the listed ones are applicable in some form in Germany and the UK. Rough revenue estimations are based on aggregated research results by Fitzgerald et al. (2015: 5).

Service	**Definition**	**Customer**	**Scheme**	**Revenue potential k€/MW/y**
Frequency control	See section 2.2.1	TSO	Market	40 -150
Spinning / non-spinning reserves	Spinning ones are operating and non-spinning ones are offline reserves for back-up generation in case of large or long duration balancing need or incident	TSO	Market / Bilateral	20 - 70
Voltage support	Reactive power to secure grid voltage level	DNO (TSO)	Market / Bilateral	20 - 50
Black start	Support power for system restoration in case of partial or full shutdown	TSO/DNO	Bilateral	< 50
Transmission congestion relief	Relieving bottlenecks in grid by levelling transmission volumes. Applicable also for distribution grid	TSO/DNO	Bilateral	N/A
Grid investment deferral	Investment postponement by providing transmission or distribution support	TSO/DNO	Bilateral	N/A
Balance handling	Keeping the energy balance between sold, bought, generated and consumed energy	Internal	N/A	N/A

Frequency control services stand out showing the highest revenue potential. They also have clearly defined customer and market based operation scheme. This makes the market penetration more attractive and business more predictable. On the other hand, applying frequency control strategy usually rules out other simultaneous revenue streams. However, also this is market specific and does not hold for instance in the UK.

3.2.2 Price arbitrage

Energy arbitrage as another revenue category is defined by Pearre and Swan (2015: 503) as transfer of electricity from low load (off-peak) periods to high load (peak) periods. Nevertheless, this study takes more economic perspective and defines it based on Zafirakis et al. (2016: 971) as shifting electricity from low price hours to hours with meaningfully higher price. Consequently, the revenues are dependent on both frequency and magnitude of the price variations (Steffen 2012: 424). Arbitrage in principle is applicable in all energy markets.

Arbitrage can be linked with both load levelling and peak shaving. Luo et al. (2015: 530) define load levelling as a method of balancing the large fluctuations in electricity demand. Thus, load levelling is considered as levelling the generation and consumption load throughout all or most of the hours while harvesting the value from respective price variation. Whereas, peak shaving concerns charging and discharging ES only between off-peak and peak hours (Luo et al. 2015: 530). As such, load levelling is a more continuous operation while peak shaving exploits only the most potential hours with the widest price spreads. Arbitrage principle in peak shaving is illustrated in figure 15.

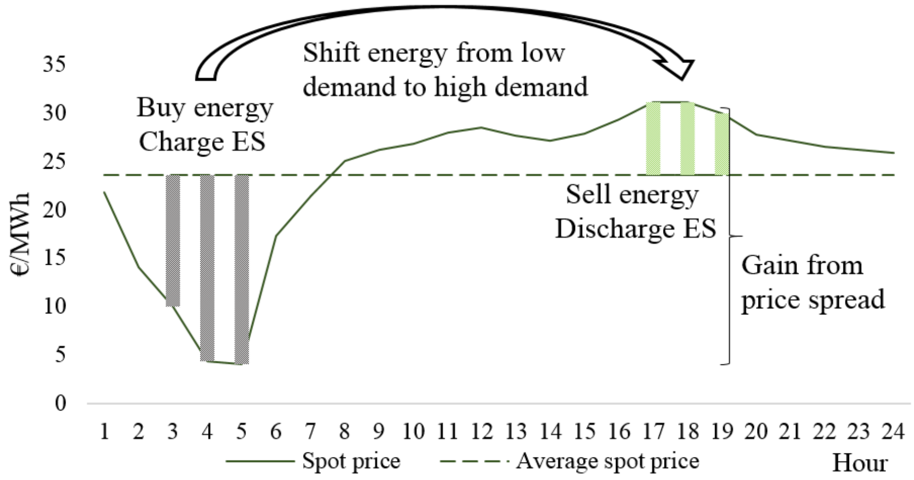


Figure 15.Arbitrage with peak shaving. Down bars illustrate charging a storage with low price whereas up bars illustrate discharging during hours with high spot price. The price level generally varies straight with system load level introducing arbitrage possibility.

Both load levelling and peak shaving can be further applied in different business models. Firstly, they can be performed purely via power exchange by bidding buy and sell bids for forecasted low and high price hours respectively. Secondly, arbitrage is a way to financially benefit from balancing intermittent renewables generation: high generation from renewables increases electricity supply and thus generally pushes price downwards. The situation is vice versa in low renewables energy source (RES) generation situation resulting in favorable price differences. Such renewables shifting can be performed behind meter directly at e.g. wind farm or via power exchange as in previous case. Nevertheless, in all conditions the revenue potential equals arbitrage value minus operating costs.

Since, arbitrage is performed for energy, the revenues are depending on the amount of shifted energy (MWh). Thus, the business model requires large energy capacity whilst large charging and discharging capacities enable exploiting the most potential price differences. Because of these requirements, and too low price volatilities in general, arbitrage has not become primary business model for BESSs. In addition, despite the anticipated need for ES for RES balancing in future, several studies have found (e.g. Zafirakis et al. 2016; Connolly, Lund, Finn, Mathiesen & Leahy 2011) that arbitrage alone does not provide sufficient revenues to justify investments in ES sector. Arbitrage in the scope of this study is treated as a secondary revenue source.

Notable is also that price arbitrage in electricity markets is market cannibalization. This is natural due to its price smoothing effect. Since, the power price in power exchange is determined purely based on supply and demand, the smoothing effect fundamentally results from decreasing variation in generation and consumption levels over time. Thus, large scale storages and increased use of smaller ones smooth the price volatility resulting in reduced arbitrage value (Sioshansi 2010: 174).

4 RESEARCH METHODOLOGY

In order to answer the research question, the study is carried out with pragmatic approach within relatively complex field including several constantly evolving aspects. To gain comprehensive insights and reliable results the assembling and analysis of the information is realized with relatively broad scope including both quantitative and qualitative data. As such, the research deals with various aspects, details and data types. Gathering, analyzing and composing the data in consistent and explicit completeness from diffuse information is thus realized with mixed research methods.

Mixed methods are methods in which both quantitative and qualitative information is used. This combination includes data collection, analysis and combination of the two datatypes in one research (Hesse-Biber 2010: 3). As such, mixed approach is especially suitable for cross-national analysis aiming to identify general patterns and analyze country specific issues (Lieberman 2005: 450). Also pragmatism is well in line with the usage of mixed methods. Indeed, Feilzer (2010: 6–16) has shown that pragmatism supports well the usage of mixed methods in order to provide useful knowledge. Feilzer states (2010: 13) that the approach is not linked to certain methods, but aims to explain any question and answer with the most suitable method. The complexity, pragmatic and comparative approach of our problem, is supporting the decision to use the mixed methods:

1. Online Market Research (OMR)
   OMR is used to gather market information and to explore and analyze the markets from various aspects. The analysis cover market functionalities, practices, characteristics and their impact on investment potential now and in the future.
2. Analytical Hierarchy Process (AHP)
   AHP is used to quantify the information obtained in OMR and to compare the markets in order to identify the most potential market for investing.

While mixed methods aim to study holistic investment and market framework, another method, Monte Carlo Simulation (MCS), is applied to complement the study by quantitatively verifying and demonstrating investment performances. As such the research utilizes multimethod approach, which is seen especially suitable for researches dealing with complex and interdependent systems (Sanders & Wagner 2011: 321). This is particularly the case in evolving new business environments. In addition, multimethod approach incorporated with multidisciplinary perspectives supports complementarity of the studied field (Sanders & Wagner 2011: 321). Ahram (2011: 288) has also pointed out that multimethod approach allows integrating "qualitatively derived, region-specific knowledge with larger cross-national, quantitative analysis in a new form of comparative area studies". Thus, using multiple methods for the study is well supported by literature. Methodology framework is shown in figure 16.

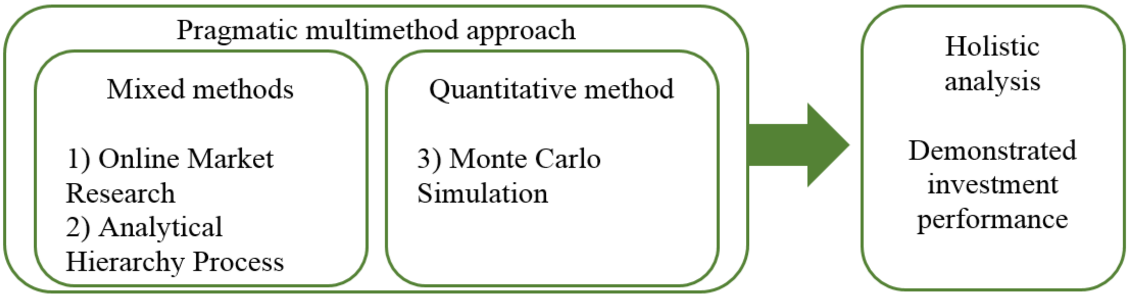


Figure 16. Methodological framework structure of the study.

4.1 Online market research

Market research in the field is naturally focused around few customers. This makes traditional online research techniques, such as target group questionnaires, obsolete. In addition, the issues explored and analyzed are rather objective considerations. Thus, the OMR is carried out by directly reaching the relevant information concerning seven high level aspects: market entry, cash flow generating potential, regulation and support policies, market size and competition, additional future aspects and risks. These aspects are further divided in ten evaluation criteria, further elaborated in next section.

4.1.1 Market evaluation criteria

The ten evaluation criteria, which are seen affecting investment potential, are all analyzed individually in case of both markets. Criteria and their factors are used for analyzing the markets and for AHP pairwise comparisons. The criteria definitions aim to avoid overlaps while providing holistic view on investment potential individually through OMR and relatively through AHP. The following defines the criteria and elaborates their factors.

1. Market structure suitability

The first criterion includes evaluating the procurement scheme TSOs use for purchasing primary frequency regulation: how suitable and supportive the scheme is for the operation in the market with BESS? The criterion considers market functionalities, liquidity / business frequency, reimbursement logic and other market structure specific issues potentially affecting the investment potential now and in future. This criterion also considers other relevant market penetration related negative and positive issues identified during the OMR.

2. Price level

The third criterion considers frequency regulation price level among the primary markets: PCR prices in Germany and EFR prices in the UK. The price level is evaluated by its absolute level and derived annual and discounted total cash flows. In addition, historical prices are analyzed in terms of development trend and volatility with expectations on the future price development. For currency conversions rate 1 GBP = 1,16 EUR is used.

3. Revenue stacking possibilities

Potential other simultaneous revenue streams are evaluated in this criterion: are there another revenue streams available and what is the cash flow impact of stacking? Also potential reasons behind unavailable stacking are discussed in order to understand potential stacking opportunity changes in future.

4. Regulation suitability

The criterion considers existing regulatory characteristics and their suitability for operating with BESS. Especially legislative recognition, treatment policies by authorities and possible regulatory unclarity issues are considered. In addition, expected future changes are taken into account.

5. Subsidies and financing

Subsidies and available public financing play a significant role in many energy investments. The criterion takes into account available subsidy policies, their significance and available public funding programmes. Financial market access or related issues are not discussed within the scope.

6. Tax and payment obligations

Net profit generation is highly related to tax and payment obligations. These issues are highly related to treatment policies and legal recognition. However, only their financial impact is examined here. In addition, potential exemptions are taken into account.

7. Size and growth

Ninth criterion analyzes the markets by their size in terms of volume and value. Realized growth and developments are also considered together with the future growth potential.

8. Competitive environment

Within this criterion both direct and indirect competition are considered. The direct competition is evaluated by registered existing and known to-be-installed BESS capacity together with capacity specifically registered for primary frequency regulation. Indirect competition includes assets other than BESS that are available to provide frequency regulation services. The capacities are compared to market sizes resulting in estimation of competition intensity.

9. Risks

Market riskiness is evaluated and compared solely by applying the risk matrices introduced later in section 4.1.4.

10. Additional future aspects

Additional future aspects include other future changes and market developments discussed through considerably speculative scenarios. The criterion excludes issues already included in previous criteria.

4.1.2 Information gathering

One of the major advantage of OMR in this case is its speed. Online sources provide possibility to close the time gap that arises with more sequential methods (Hesse-Biber & Griffin 2012: 58). Thus, it is possible to access the most recent information simultaneously from various sources, which is important due to rapidly evolving markets. The method also provides very large information pool to be exploited.

Market research information for further analysis is collected from various sources. Online sources are supported by related literature and direct discussions with relevant professionals and authorities. The main sources for both countries include:

1. TSO's web pages, grid codes and straight contacting via email and phone
2. Online documents published by authorities, governments and the European Union
3. Separate market studies, reports and related academic papers
4. Other stakeholders such as national investment agencies and market participants.

4.1.3 Information reliability

One of the major concern with OMR method is information reliability. The study aims to improve information reliability by comparing alternative sources when possible. The confirmations are also sought from authorities and industry professionals via emails, calls and discussions. However, this issue is addressable also as a pitfall: using online tools for contacting interviewee might disrupt the information gained when compared to e.g. personal visit (Hesse-Biber & Griffin 2012: 58). This disrupting effect is limited by preferring objective and fact driven questions.

In order to improve information reliability even further, available information from sources potentially affected by subjective interests are discarded. However, it is relevant to underline that the study is dealing with relatively new field involving immature legislative and regulatory frameworks, limited references and dynamic market development. Thus, in some instances desirable information cannot be confirmed or it might not even exist.

4.1.4 Risk matrices

The ninth criterion, market riskiness, in OMR is estimated by evaluating the five most relevant risks for each country. The evaluation is made with risk matrices. Risk matrix is a widely used model to evaluate the occurrence probability and impacts of risks, and rank the risks respectively (Fouad & Jabir 2015: 1188). The matrix is two-dimensional evaluation framework that is used to assess separately risk occurrence probability and impact. The evaluation is usually based on quantitative evaluation. However, the risks can be quantified with indicative numerical estimators assigned for each qualitative value. Identified risks in this study are quantified like this. Used matrix structure, risk impact and probability descriptions with quantification estimators are elaborated in tables 7–9.

Table 7. Risk impacts with assigned values and descriptions (based on Fouad & Jabir 2015: 1189).

Risk Impact	Estimator	Description
Critical	5,0625	Risk results directly to the market potential vanishing
Serious	3,375	Risk leads to a significant decrease in market potential
Moderate	2,25	The market moderately affected , but potential partly remains
Minor	1,5	The market is slightly affected, but could satisfy investment evaluation
Negligible	1	Risk has almost no effect on market potential

Table 8. Risk probability with assigned values and descriptions (based on Fouad & Jabir 2015: 1189).

Risk Probability	Estimator	Description
0–10%	0,05	Almost impossible to occur
11–40 %	0,25	Unlikely occurring
41–60 %	0,5	Moderate likelihood for occurring
61–90%	0,75	Likely occurring
91–100 %	0,95	Almost certainly occurring

Table 9. Risk matrix with derived risk value indicators calculated as product of estimators of occurrence probability and impact shown in tables 7 and 8.

	Risk Impact				
Risk Probability	Negligible	Minor	Moderate	Serious	Critical
0–10%	0,05	0,08	0,11	0,17	0,25
11–40 %	0,25	0,38	0,56	0,84	1,27
41–60 %	0,50	0,75	1,13	1,69	2,53
61–90%	0,75	1,13	1,69	2,53	3,80
91–100 %	0,95	1,43	2,14	3,21	4,81

Only market specific risks are concerned in order to provide more consistent approach for market comparisons. Thus, for instance technology related risks are not analyzed here. Nevertheless, considering five most relevant risks, the overall risk index scale is from 0,25 (5 X 0,05) to 24,05 (5 X 4,81) based on the values in table 9.

4.2 Analytical Hierarchy Process

In order to compose comparative investment potential among the explored markets Analytical Hierarchy Process (AHP) is applied. AHP is a structured tool for dealing with complex decision making (Erol & Kılkış 2012: 246). AHP provides systematic approach to evaluate alternatives by several quantitative and qualitative criteria. The method does not provide straight answers, but results in ranking giving information which is the most suitable from available alternatives for the underlying problem (Erol & Kılkış 2012: 246). The method was initially modelled in 1980 by Saaty (Saaty 1980).

AHP allows efficiently considering decision maker’s subjective opinions (Subramanian & Ramanathan 2012: 217). The method shows its strengths when several people are considering complicated problems based on their human perceptions and judgements (Erol & Kılkış 2012: 246). However, it is suitable also for straightforward decision making by individual analysts (Erol & Kılkış 2012: 246). In this research AHP is used in individual means with consulting contribution from industry professionals. It is used as mixed method to compose OMR results in relative investment potential evaluation and ultimately provide information regarding relative market potentials in the UK and Germany.

4.2.1 Process phases

General AHP approach follows three steps: problem structuration, pairwise comparisons and global priority composition. The steps are illustrated in figure 17 (Saaty 1990: 14–18). The steps are elaborated below with simultaneous AHP model structuration for the underlying study.

Figure 17. General steps in Analytical Hierarchy Process.

Step 1: Structuring the problem as hierarchy

AHP starts from dividing the problem in three hierarchical levels. The first level includes an ultimate goal of applying the method. The goal is followed by criteria and sub-criteria level which sets the factors contributing to the goal. The third level includes alternative candidates which are evaluated against the goal based on the criteria. (Saaty 1990: 14.)

In the case of this study, the first level goal is to identify the most potential market for BESS investment. The second level is divided in criteria and sub-criteria in order to consolidate relevant criteria groups together for more consistent analysis. These criteria are the ones introduced in section 4.1.1. The hierarchy structure is illustrated in table 10.

Table 10. AHP Hierarchy structure for investment potential evaluation. Numbering refers to ten chosen market evaluation criteria.

Level 1 Goal	Identify the most potential market for BESS investment					
Level 2 Criteria	1. Market scheme suitability	Cash flow generating potential	Regulation and policies	Market size and competition	9. Risks	Future outlook
Sub-criteria		2. Price level 3. Revenue stacking possibility	4. Tax and payment obligations 5. Regulation suitability 6. Subsidies and financing	7. Size and growth 8. Competitive environment		10. Additio-nal future aspects
Level 3 Alternatives	Germany			the UK		

Step 2: pairwise comparisons

The second step's pairwise comparisons concern both criteria and alternative levels from the hierarchy structure. At first a matrix (A) for comparing the criteria is created. The matrix is fulfilled by relative criteria importance judgements (e_{ij}) based on pairwise comparisons. The judgements are answers to a question: which of the two criteria compared, is considered more important with respect to the goal (Saaty 1990: 15). A standard comparison scale, elaborated in table 11, is used in order to quantify the judgements. If criteria i is more important than j, $e_{ij} > 1$, and vice versa. Respectively, since A compares the same criteria reversely, it can be defined that $e_{ji} = 1/e_{ij}$.

Table 11. Evaluation scale for pairwise comparisons (Saaty 1990: 15).

Importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible
1,4,6,8	Intermediate values	When compromise is needed

After composing the comparison matrix normalized matrix A_{norm} can be derived. Entry values E_{ij} for A_{norm} are e_{ji} values normalized by the column sums in A and can be calculated as in equation 2. A_{norm} gives the normalized relative weights for each criteria.

$$E_{ij} = \frac{e_{ij}}{\sum_{k=1}^{n} e_{kj}}, \qquad (2)$$

where k is the row number in column in A and n is the number of the criteria.

Output from the comparison is a priority vector, normalized eigenvector w, giving relative weights w_i for the criteria. From A_{norm} normalized eigenvector w is calculated as row averages (Al-Harbi 2001: 24). Structure of the matrix A including derived eigenvector w is illustrated in table 12. A for the criteria in our problem is illustrated in table 13. Numbering refers to criteria numbering in hierarchy structure in table 10.

Table 12. General structure of a AHP pairwise comparison matrix A.

	Crit. 1	Crit. 2	Crit. j	Priority (w_n)
Crit. 1	1	e_{12}	e_{1j}	w_1
Crit. 2	1/ e_{21}	1	e_{2j}	w_2
Crit. i	1/ e_{i1}	1/ e_{i2}	1	w_i
Sum	$\sum e_1$	$\sum e_2$	$\sum e_j$	1

Table 13. Pairwise comparison matrix and derived priority vector w used in the study. Numbering in x and y -axis refers to investment potential evaluation criteria numbering.

n	1	2	3	4	5	6	7	8	9	10	W_n
1	1,00	0,50	5,00	4,00	3,00	5,00	6,00	3,00	5,00	6,00	21,67 %
2	2,00	1,00	5,00	4,00	3,00	5,00	6,00	3,00	5,00	7,00	25,52 %
3	0,20	0,20	1,00	0,50	0,33	1,00	1,00	0,17	0,33	2,00	3,63 %
4	0,25	0,25	2,00	1,00	0,50	2,00	4,00	0,50	3,00	4,00	8,09 %
5	0,33	0,33	3,00	2,00	1,00	2,00	5,00	0,33	4,00	5,00	10,78 %
6	0,20	0,20	1,00	0,50	0,50	1,00	3,00	0,25	0,50	1,00	4,25 %
7	0,17	0,17	1,00	0,25	0,20	0,33	1,00	0,20	1,00	2,00	3,20 %
8	0,33	0,33	6,00	2,00	3,00	4,00	5,00	1,00	5,00	4,00	15,24 %
9	0,20	0,20	3,00	0,33	0,25	2,00	1,00	0,20	1,00	2,00	4,91 %
10	0,17	0,17	0,50	0,25	0,20	1,00	0,50	0,25	0,50	1,00	2,71 %

Identically matrices for the alternative solutions are formed. At this lower level the alternatives are evaluated against each underlying criterion. Thus, there are in total 10 such 2 X 2 matrices in our case. Priorities, i.e. derived eigenvector values (w_n), for the alternatives in case of each criterion are called local priorities ($L_{m\ n}$).

Step 3: compose global priorities

The final step is to compose global priorities for the alternatives based on local priorities ($L_{m\ n}$) and the normalized eigenvector values (w_n) of the criteria. The local priorities are multiplied by the criteria priorities and summarized for each alternative. Global priority W_m for alternative m is calculated as in equation 3. The composition matrix is illustrated in table 14. Finally the global priority vector W allows ranking the alternatives and giving recommendation of the most suitable alternative.

$$W_m = \sum_{n=1}^{n}(w_n L_{mn}), \quad (3).$$

Table 14. Composition matrix for deriving global priorities. $L_{m\,n}$ represents local priorities for alternatives in case of each criterion, w_n the weight of each criterion and W_m ultimate priority vector showing the composed results.

	Crit. 1	Crit. 2	Crit. n	Global
	w_1	w_2	w_n	W
Alternative 1	L_{11}	L_{12}	L_{1n}	W_1
Alternative 2	L_{21}	L_{22}	L_{2n}	W_2
Alternative m	L_{m1}	L_{m2}	L_{mn}	W_m

4.2.2 Consistency

Logical relevancy of the pairwise comparison result must be confirmed in order to ensure reliable results. The consistency check ensures that there are no unacceptable amount of logical errors disrupting the results. Logical error occurs e.g if alternative A is evaluated to be more important than B, B more than C and C more than A. Formally, the consistency means linearly independent comparison matrices (Franek & Kresta 2014: 167).

Consistency is measured by consistency ratio. After composing the comparison matrix and eigenvector the ratio is obtained in three phases:

1. Calculate the highest eigenvalue (λ_{max})
   λ_{max} is obtained from weighted sum vector, calculated as Aw, by dividing each element of the vector with respective element from priority vector w. λ_{max} is average of these values. Franek and Kresta (2014: 167) represent this as a sum function as in equation 4:
   $$\lambda_{max} = \sum_{j=i}^{m} \frac{(A \cdot w)_j}{m \cdot w_j}, \quad (4)$$
   where m is the number of rows in matrix A.
2. Calculate consistency index (CI)
   CI is calculated as in equation 5 (Saaty 1990: 13):

$$CI = \frac{\lambda_{max} - n}{n-1}, \tag{5}$$

where n is the number of the criteria (alternatives).

3. Calculate consistency ratio (CR)

   Finally CR is obtained by dividing CI with ratio index (RI) (Saaty 1990: 13):

$$CR = \frac{CI}{RI}, \qquad (6).$$

The RI -value represents average of CI values derived from random pairwise-comparison matrix simulations (Franek & Kresta 2014: 167). CR value over 0,1 is not accepted. This is also the suggested inconsistency limit by Saaty (1990: 13). For RI value average (1,48 for n=10) from various results collected by Franek and Kresta (2014: 168) is used. Consistency is applicable when determining the criteria weights. The ratio for matrix in table 13 is 0,056 and thus accepted. For pairwise comparison under each criterion consistency check is not relevant as 2 X 2 matrix is consistent by nature: there is only one subjective comparison to make under each criterion.

4.3 Monte Carlo simulation

The third applied method is Monte Carlo simulation. It is a numerical method used for solving problems incurring complex uncertainties that are problematic for analytical solving. As such, it supports well investment performance research as the target business and markets involve significant uncertainties themselves. The foundations of the method rely on variation in input parameters that are derived from estimated probability distributions by using random sampling. The variation, i.e. uncertainty, in inputs is modelled in problem specific model in order to calculate desired output values. The calculations are iterated numerous times to turn input distributions to output distribution through the model. Thus, the method provides a possibility for exploring and demonstrating various scenarios and input uncertainties with respective outputs. The method has evolved to a widely used tool in quantitative research across industries and applications (Kroese, Brereton, Taimre & Botev 2014: 386). General three phased MCS approach is illustrated in figure 18 and further elaborated below.

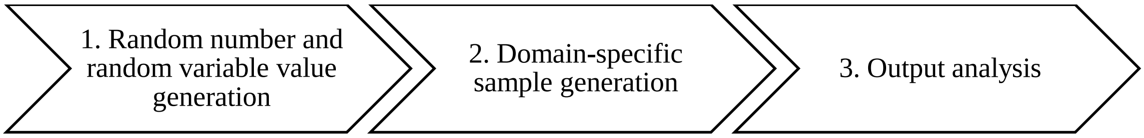


Figure 18. General approach for MCS method (based on: Brandimarte 2014: 254).

1. Random number generation imitates actual uncertainty involved in underlying problem (Brandimarte 2014: 254). These pseudorandom numbers are usually uniformly distributed with range of 0–1. The range is sufficient since MCS is dealing with probabilities, whilst uniform distribution allows introducing variable specific distributions later. The random numbers are used to pick a value from determined random variable distributions. These random variables are the model inputs and the distribution reflects respective uncertainties and stochasticity.
2. The second phase includes actual iterative simulations. In this phase the random variable values and respective target function values are simulated iteratively in order to gain samples for desirable outputs. The simulation model includes random numbers, random variable values and possibly various other derived variables and constants in order to calculate desired output variable values.
3. Finally output analysis is performed in order to explore output values, their distributions and behaviors. In addition, the analysis is necessary for model validation and verification to ensure reliable results (Brandimarte 2014: 325).

4.3.1 Approach in this study

In order to illustrate market specific possible BESS investment financial performance and to support decision making in an uncertain environment the study utilizes a country specific approach. As the markets are differing largely, the approach also allows exploring profitability boundary conditions more effectively. In addition, numerous simulations capture a range of random input scenarios and thus make the results free from objective scenarios. Thus, MCS also provides more complete and coherent information.

MCS in the study aims to explore possible BESS investment profitability, financial performance and required profitability boundary conditions and thus validate and quantify prevailing market research results. The issues are explored by simulating BESS market operations for 15 year investment horizon, determining revenues and costs, deriving investment valuations for each iteration and finally analyzing output distributions. Applied key outputs for investment performance evaluations are free cash flow (FCF), net present value (NPV) and internal rate of return (IRR). NPV is calculated as real value without inflation adjustments. The approach is illustrated in figure 19.

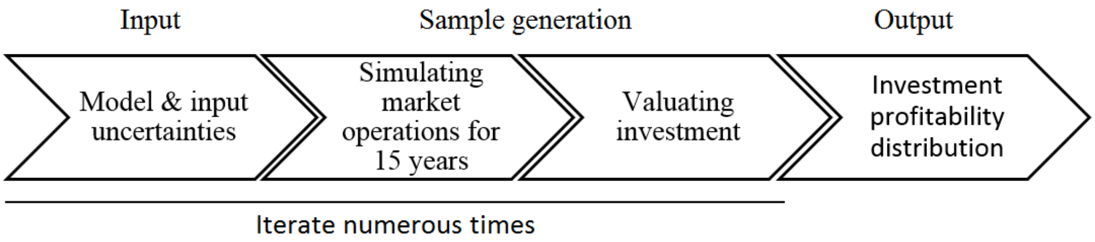


Figure 19. MCS approach in the study.

The models are formulated based on market characteristics. Used random variable probability distribution functions for the simulation models are derived by fitting several types of commonly used distributions to publicly available historical data in R –program and choosing the most relevant one. The fitting is done by maximum likelihood method for parameter estimations. The results are validated with histogram method by visually checking the fittings of theoretical probability distribution functions in real data. The method is rather robust, but is applicable only for random variables with historical observations. For variables without available data, the distributions are estimated by the researcher to the best of his ability. Actual simulation models are built in VBA -code and run in spreadsheet program.

4.3.2 Simulation model – Germany

German MCS model is based on the market scheme discussed in section 2.3. The model is built from national perspective and thus import/export limitations for the joint tenders are not included. Respectively only national historical PCR prices are taken into account. The applied business model involves primarily operating in PCR market and if bid is not accepted, secondary revenues stream, spot arbitrage, is applied for "out of PCR" period. Model framework is illustrated in figure 20 and further elaborated below in six phases. Additional assumptions used in the final model are represented in section 4.3.2.

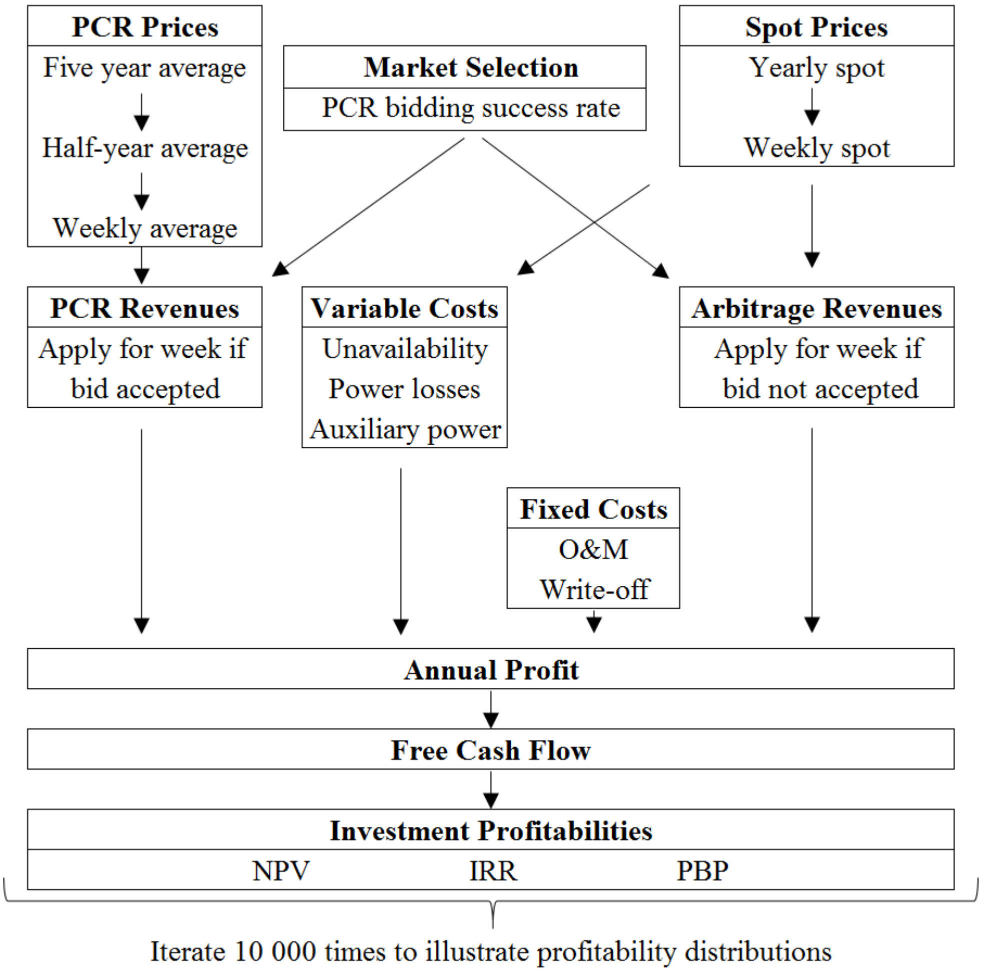


Figure 20. Monte Carlo Simulation model framework for Germany. The arrows illustrate causalities between inputs and outputs.

Phase 1: Market selection

Market selection uncertainty determines probability for operating in overriding PCR market. Success rate in PCR tenders is a critical factor in revenue generation and is highly dependent on applied bidding strategy. The probabilities for successful bidding with different bidding strategies were estimated by taking a base price for bids from the previous week$_{n-1}$ realization, scaling it by percentual ± changes and checking whether the reached price is less than accepted maximum bid price in the next auction for week$_n$. For the base price, realized auction average, median, minimum and maximum values from week$_{n-1}$ were applied. In addition, strategy with a seasonally adjusted average data was applied. Seasonality is illustrated later in figure 46. Furthermore, strategy examination with historical values from longer than previous week horizon was applied, but the results favored looking only in the previous week's realization. Bid acceptance probabilities, i.e. success rate, for the strategies and percentage scaling are illustrated in figure 21.

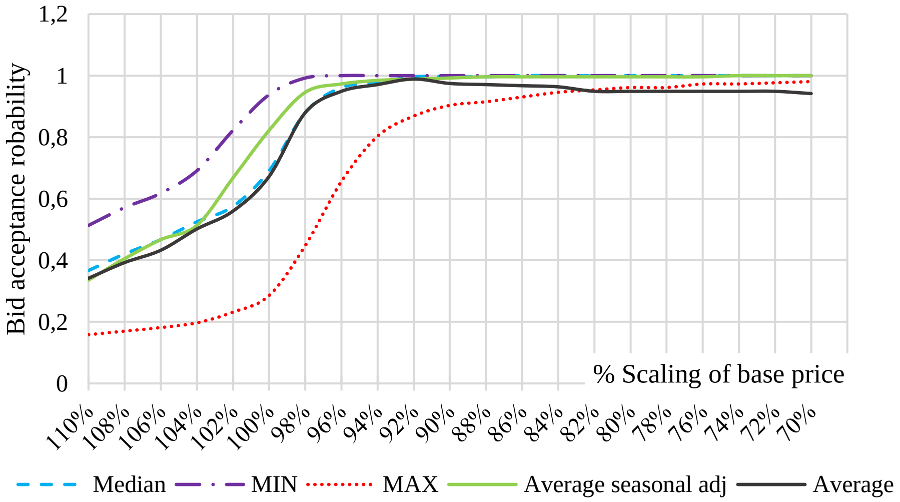


Figure 21. Calculated bid acceptance probabilities in German PCR market when hypothetically bid with different bidding strategies based on scaled realized weekly median, minimum, maximum, seasonally adjusted and arithmetic mean PCR prices.

Bidding strategies were also examined in terms of weekly average spot prices. In fact, statistically significant linear relationship (p-value = 5,8E-06) was identified between spot and PCR prices, but with negligible adjusted R-square of 0,073. In addition, the change direction between the prices were same only in 53 % of the weeks. Thus, adjusting the bids with spot price forecasts, even with 100 % accuracy, doesn't provide sufficient additional accuracy in PCR bidding.

Besides the applied bid the spread between minimum and maximum in price realization plays another key role in successful operating: priority is to get accepted while not under valuating the bid. Thus, the price spread determines effective bidding range. Nevertheless, the spread is hard to forecast as it materializes all expectations, consensus level among the traders, market participant specific opportunity costs and participation willingness. As such it has varied by level significantly over time. In addition, the variation range follows only very fuzzy pattern of peaks during the first weeks of the year and in summer – as does the average prices. Realized spreads are illustrated in figure 22.

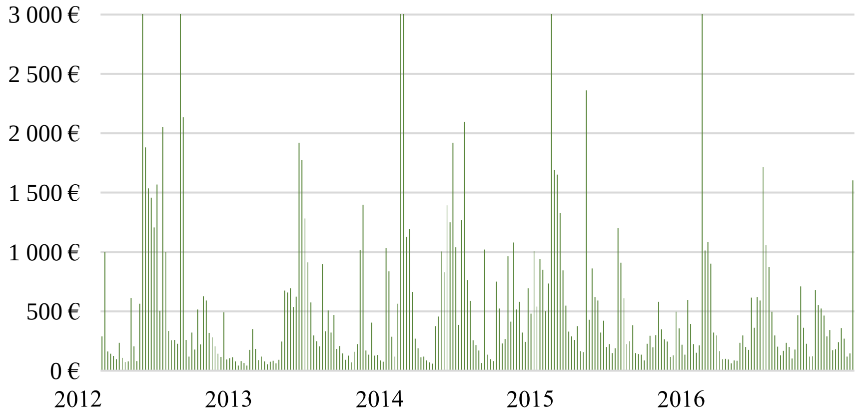


Figure 22. Price differences between realized minimum and maximum accepted PCR bids in Germany. Y-axis is limited as one of the peaks reaches over 18 k€. Other peaks outside the scale reach around 4000–6000€. (Data: Regelleistung.net 2017f.)

Naturally, the success rate has a major role in PCR revenue gaining. Nevertheless, the tradeoff between high price and low acceptance probability has optimum as decreasing price does not provide infinite success increase. Indicative annual average PCR revenues with 2012–2016 prices and applied bidding strategies are illustrated in Figure 23.

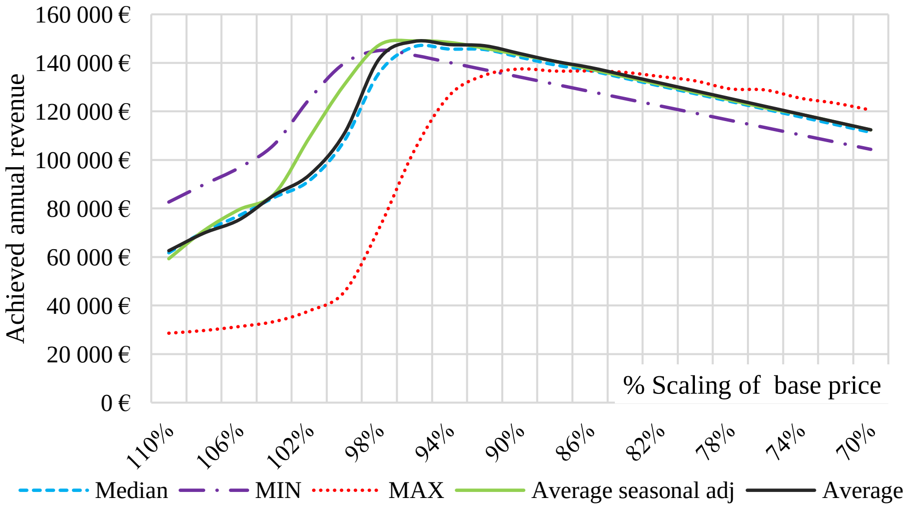


Figure 23. Annual average PCR revenues with 2012–2016 prices when hypothetically bid with different strategies based on scaled realized weekly median, minimum, maximum, seasonally adjusted and arithmetic mean prices. (Real data: Regelleistung.net 2017f.)

The best bidding strategy identified is bidding 95 % of seasonally adjusted average price from the previous week realization. The strategy yields in average of 149 k€/year from PCR market with 98 % success rate. However, using deseasonalized average prices by adjusting the previous week's value with 0,96 yields in only 0.2% lower revenues with 95 % success rate. Since MCS values are simulated from distributions instead of time series, the method ignores auto-regression between the weekly values. Thus, applying seasonal adjustments is problematic in this case and for MCS the average strategy (95 % success rate by bidding 96 % of previous weekly average price) is used as base scenario.

The success rate can be seen high even with purely theoretical examination. Nevertheless, the approach ignores trader's view, dynamic effects of new bids and assumes price taker role. The effects from price taker role and dynamic market changes in are invalidated by using small BESS as reference investment. Trader's contribution is ignorable due to only 5 percentage point improvement potential in success rate. However, notable is that the annual cash flows in figure 23 are very similar to the probability graphs in figure 21. Such situation involves clear risk as the best revenues are reached with less than average prices: collective rational bidding could decrease the prices significantly in a short time period.

Phase 2: PCR prices

PCR price distributions are estimated from realized German national price data 2012–2016. Weekly prices in MCSs are simulated through three levels of uncertainty: average five year, average half year and weekly average PCR prices. Half-year periods are used due to relatively short history of data, i.e. small number of observations, resulting in poor distribution estimation reliability otherwise. Half year and weekly variation distributions are derived from historical data whilst for five year average prices estimated uniform distribution is used (U [2700; 3500]). The distribution estimation is based on realized annual variation range 2012–2016.

Half year average price level distribution is estimated from relative values achieved by dividing realized half-year averages with average of the whole five year horizon. This makes the results applicable with different five year values generated. Results for gamma, lognormal, Weibull and normal distribution fits are illustrated in figure 24. Already after a visual check it is clear that the distribution estimations provide only rough estimations with questionable fit. The problem is especially the small number of observations. However, cumulative density function graph shows acceptable results with the best fit achieved by lognormal distribution with parameters LOGN[-0,0110939; 0,1461308].

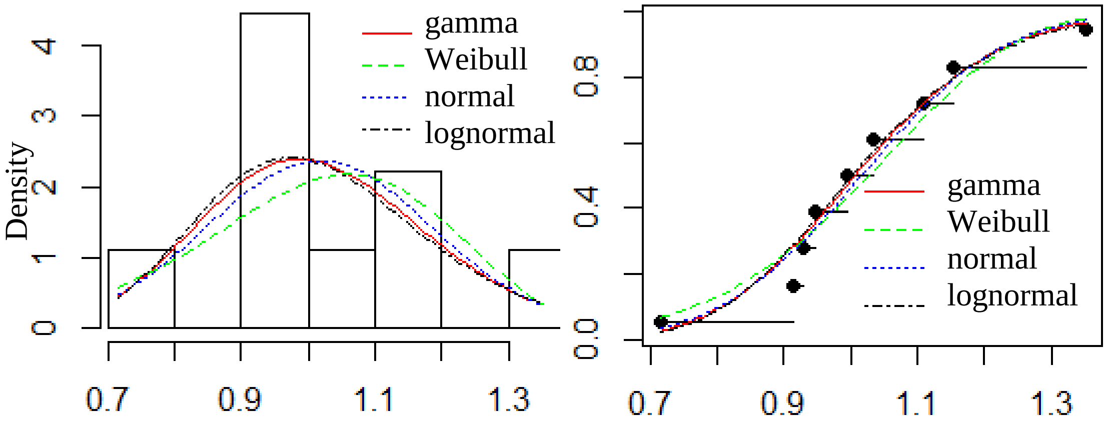


Figure 24. Distribution fit illustrations on left for relative half-year average PCR prices with theoretical fits and realization data. Respective cumulative density function on right. (Real data: Regelleistung.net 2017f.)

Distribution for weekly fluctuation around the half-year average is similarly estimated from relative figures by fitting the theoretical distributions against realized weekly values divided by half-year average. The distribution and theoretical fitting results are illustrated in figure 25. The distribution fits are relatively good while lognormal distribution with mean of 0,002446947 and standard deviation of 0,167208033 provides the best results.

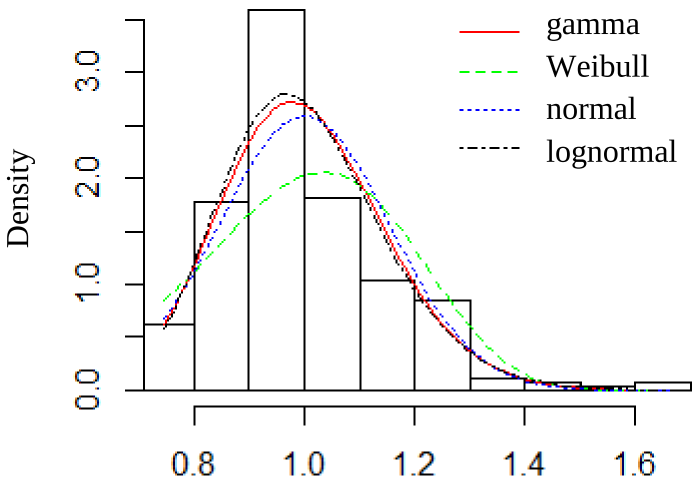


Figure 25. Distribution fit illustration for relative weekly PCR price distribution around half-year average PCR prices. (Real data: Regelleistung.net 2017f.)

Phase 3: PCR price simulation validation

Relevancy of using the approach of three distributions is confirmed by simulating prices with prevailing parameters. The results from 10 random simulations for a five-year horizon and realized price data 2012–2016 sorted in descending order are illustrated in figure 26. Real and simulated plots follow each other relatively well and the average price difference between real and average of the simulated values is 2,0 %. In addition, figure 27 illustrates annual average price realization fluctuation limits and simulation results for one random simulation. The figures confirm that the simulated prices fluctuate at relevant level both on weekly and annual level and thus support using the distributions for MCS. The illustrated deviation from realization is desirable since the future is unknown.

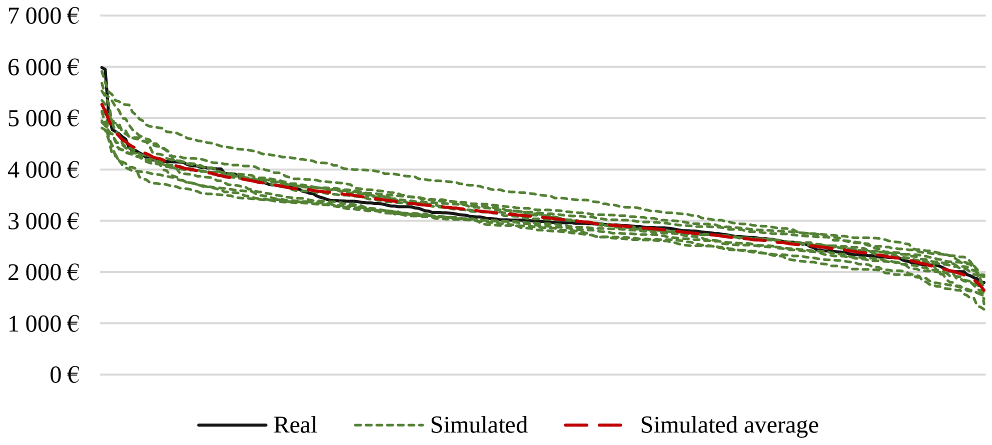


Figure 26. Real PCR prices 2012–2016 and simulated prices from lognormal distributions in descending order. Simulated five year average is set to realized average. (Real data: Regelleistung.net 2017f.)

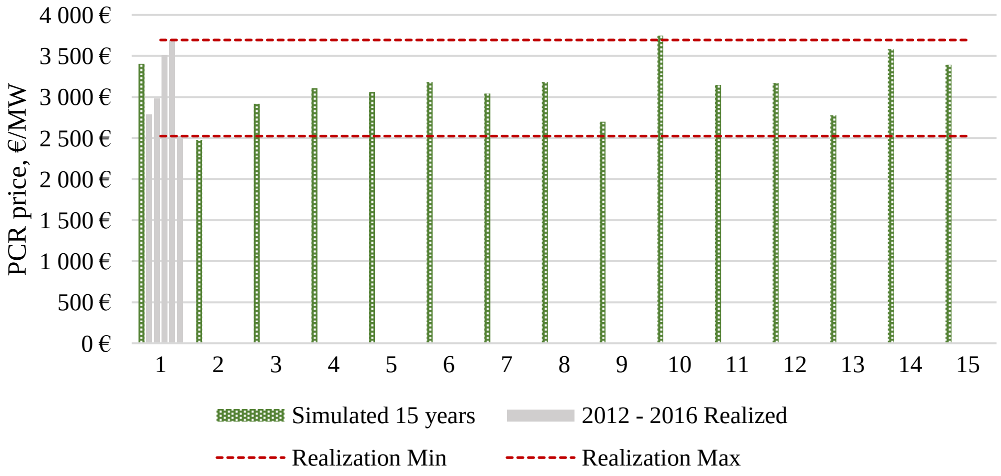


Figure 27. Annual PCR prices for 15 years from one random simulation validated against 2012 - 2016 realization limits. Simulated five year average is set to realized average. (Real data: Regelleistung.net 2017f.)

Phase 4: spot price

Spot price in the model is affecting arbitrage revenues and variable costs. It is modelled in two levels: yearly and weekly average level. Annual figures are based on uniform distribution (U[26; 39]) and its parameters are based on 2012–2016 realization (min 29,01, max 42,60) adjusted with realized decreasing spot price trend (data: eex.com 2017). Weekly price is then simulated from normal distribution (N[0,9955139; 0,2005347]), that determines the weekly variation around the annual average. Normal distribution parameters are estimated similarly in R as earlier.

Relevancy of the estimations is confirmed visually as illustrated in figure 28. Simulation results for weekly spot prices for a whole 15-year horizon are shown with 2012–2016 realization. Simulated prices have somewhat higher volatility, but this mainly results from a lack of time-dependencies in simulations. Nevertheless, the issue is diluted when the values are summarized in valuation calculations. All in all, the results show that price level and variation range are applicable for MCS with mentioned distributions.

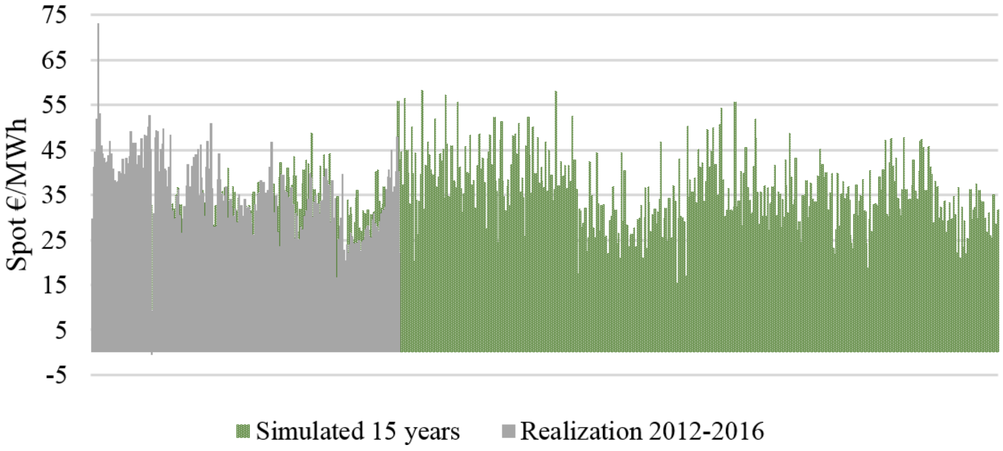


Figure 28. Simulated time-independent weekly spot prices for 15 years validated against time-dependent realized prices 2012–2016 (real data: eex.com 2017).

Phase 5: Arbitrage revenues

Simulated spot price determines base level for arbitrage value. However, due to the lack of time-dependencies and large weekly resolution, actual arbitrage revenues are not calculated from spot prices, but from arbitrage value distribution. Arbitrage value here means potential arbitrage profits during a one-week period. The distribution is estimated by calculating a weekly arbitrage value for 1 MW / 1 MWh BESS from hourly spot prices in 2012–2016. The weekly arbitrage values were calculated by applying an arbitrage algorithm from Connolly et al. (2011: 4195) for 24 hours ahead.

The algorithm is based on determining maximum price hour in given time horizon and determining minimum price hour in relevant range around the maximum hour. The difference between the prices determine arbitrage value from shifting energy from minimum to maximum hour. Based on these price differences and BESS power and energy capacities, the algorithm determines charging and discharging hours. Weekly arbitrage profits are calculated by summarizing these individual values. The algorithm was translated in VBA -script and utilized in spreadsheet program for calculations. The algorithm is represented in figure 31. Detailed information is available in the original article (Connolly et al. 2011). The algorithm with day-ahead approach is shown to harvest 97 % of the optimal arbitrage potential (Connolly et al. 2011: 4190).

The resulting arbitrage values give absolute arbitrage revenue distribution. However, there is a slight linear relationship between weekly spot average and arbitrage revenue. P value for linear regression between the two is 0,137 and thus too large for deriving arbitrage values straight from simulated spot prices. However, the slight linear relationship and arbitrage revenue uncertainties are captured by dividing weekly arbitrage values by respective weekly spot average. This arbitrage ratio ties arbitrage level to simulated spot prices, but allows modeling the variation around the average. Thus, it allows reliably deriving arbitrage revenues with different simulated spot price levels. Arbitrage ratio distribution and distribution fits are illustrated in figure 29. The best distribution fit is reached with lognormal distribution (LOGN[2,1617867, 0,3572595]).

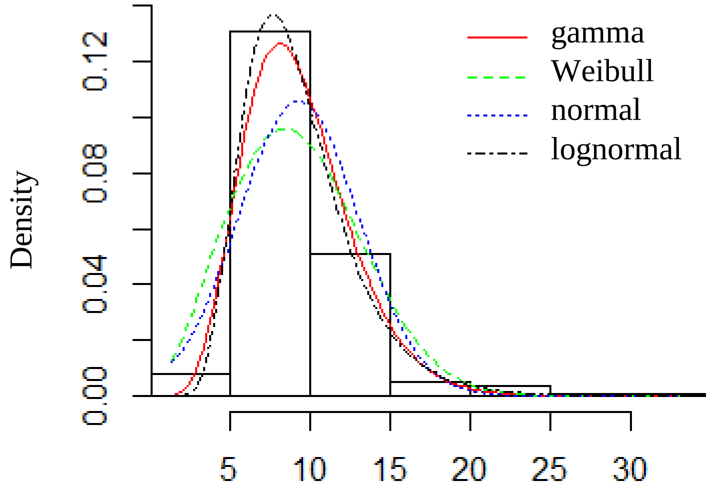


Figure 29. Empirical arbitrage ratio (weekly arbitrage profits / weekly spot average) distribution calculated from 2012–2016 German spot prices illustrated with theoretical distribution fits (real data: eex.com 2017).

The approach and applied distribution are validated with random simulations for five-year horizons as illustrated in figure 30. The model gives slightly higher revenues at the higher half of the revenue distribution. However, majority of the simulated values are very close to realized values. In addition, with 95 % success rate, arbitrage represents insignificant share in total revenues. Thus, the bias has very small effect on overall model output and the arbitrage modelling is accepted for MCS.

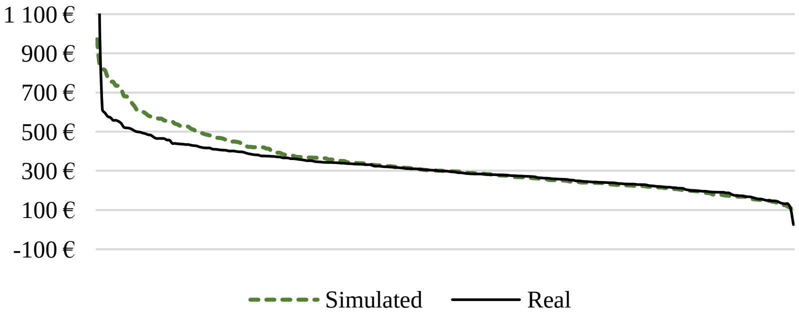


Figure 30. Simulated five year and realized (2012–2016) arbitrage values in descending order for Germany (real data: eex.com 2017).

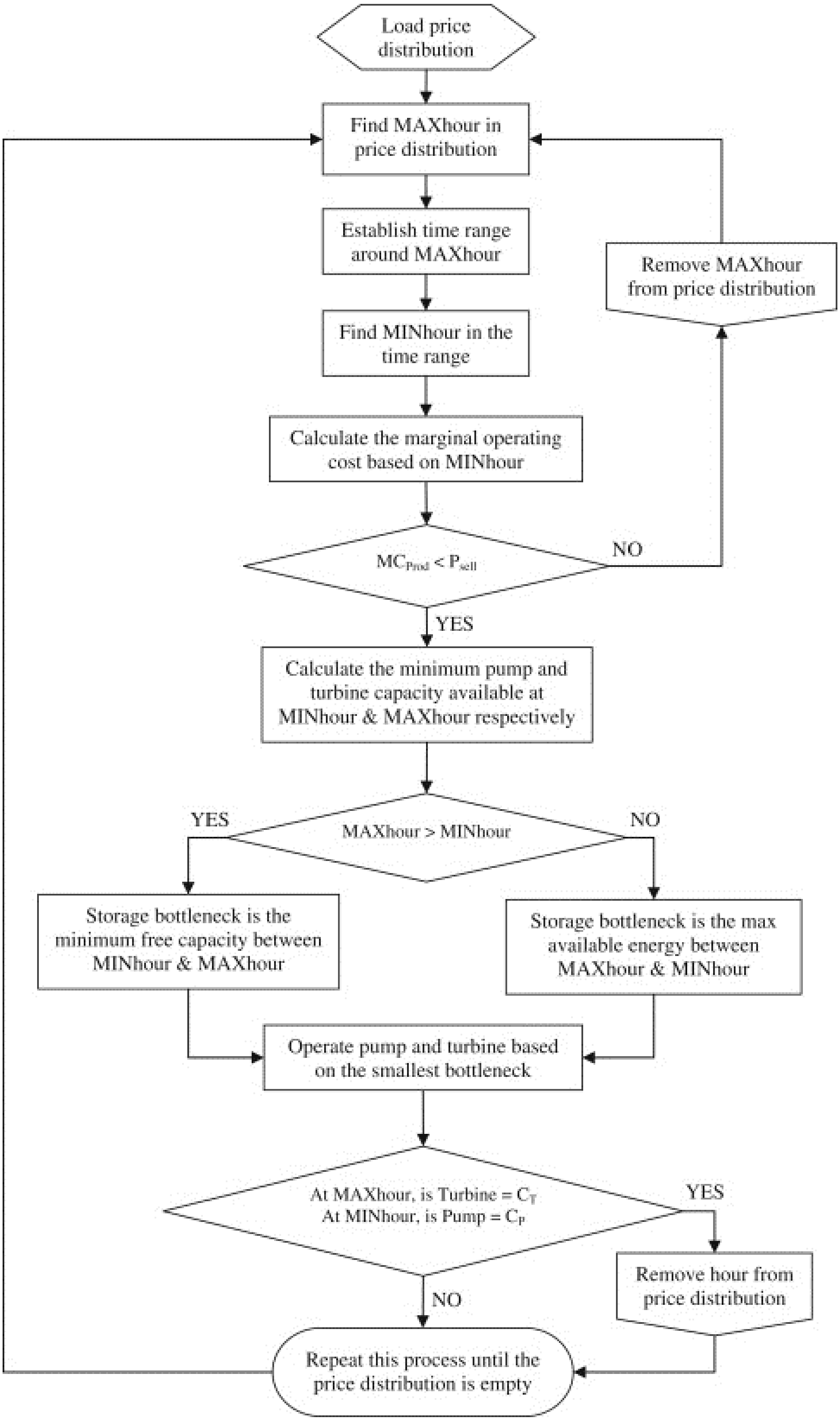


Figure 31. Algorithm for calculating time-shifting arbitrage revenues (Connolly etc. 2011: 4195).

Phase 6: Model validation

Composed model validation is performed by evaluating cost and revenue structure, levels, and variations. Figure 32 shows revenue and cost factors for one random simulation for 15 years. Whereas, figure 33 shows free cash flows for 15 years from 50 simulations with density function. The figures illustrate valid cash flow levels with relevant variation. The same applies to cost factors. In addition, revenue/cost ratio is relevant for such capital intensive investment while annual free cash flow variation and output distribution is well in line with the expectations. Thus, the results confirm the model relevancy.

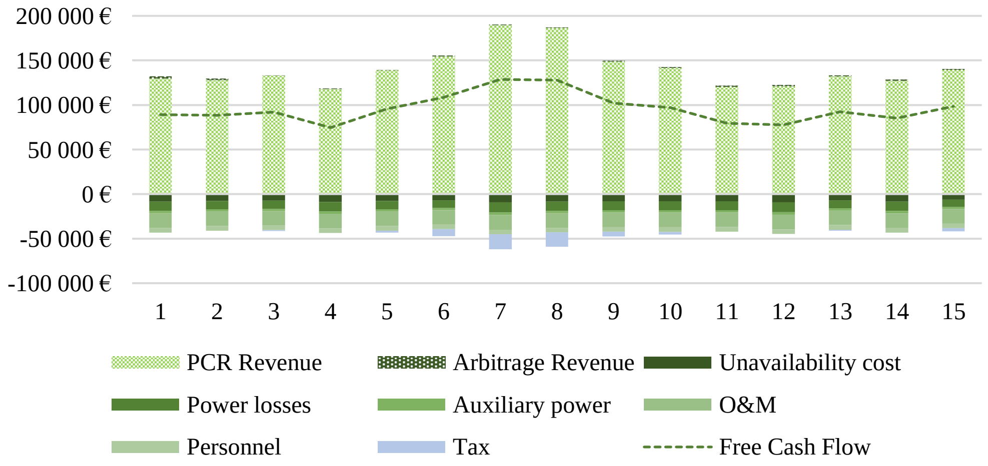


Figure 32. Simulated cost and revenue structure with respective free cash flow for 15 years for one random simulation for German PCR market.

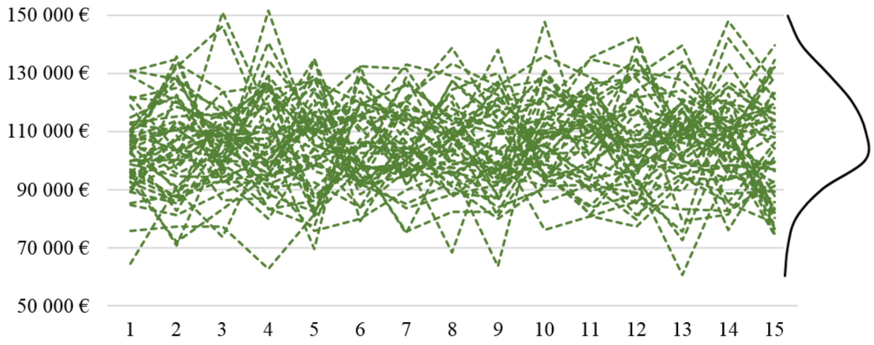


Figure 33. Free cash flows from 50 simulations for 15 years with respective density function for German PCR market.

4.3.3 Simulation model – the UK

MCS model for the UK is based on an assumption of a yearly EFR market in the future. The assumption is made based on TSO’s anticipation of the future developments and will be further discussed in chapter 5. The integrated revenue stacking opportunities from the capacity market are another major difference to the German model. Otherwise the model approaches and applied business models are identical. MCS model framework for the UK market is illustrated in figure 34. The parts are discussed below in 6 phases while additional assumptions used in the final model are represented in section 4.3.4.

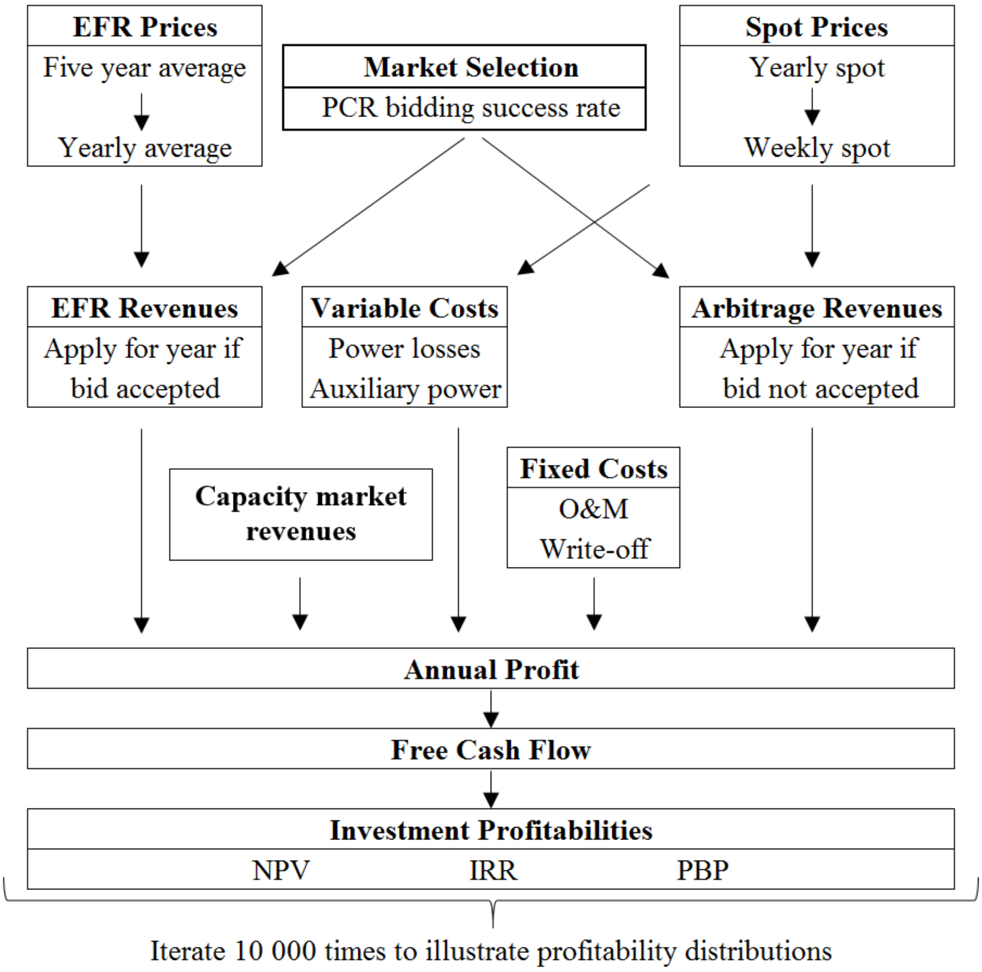


Figure 34. Monte Carlo simulation model framework for the UK.

Phase 1: market selection

Market selection and success rate in the UK is evaluated from the initial 2016 EFR tender bids. The lowest accepted price was 7 £/MW/h and by bidding minimum price the success rate is regarded as 100 %. On the other hand, the total bidding volume was slightly more than 5100 MW with average price of 21,70 £/MW/h. Volume of accepted bids represent 3,9 % of all bids and this is regarded as low end of success rates. Prices 7–21,70 £/MW/h and respective success rates 100–3,9 % are filled linearly and expected total returns are calculated for 15 years as product of amount of total hours, success rate and respective hourly price. The best result is reached with bidding price 11,41 £/MW/h, which yields in 71,2 % success rate. This rate is used as a base rate for MCS. Of course this is a very artificial estimation, but gets support from tender realization: the highest accepted price was very close to prevailing optimal bidding price. In addition, since the competition is fierce among BESSs in EFR, it is relevant to assume that the success rate in future is clearly lower than in German auctions. EFR tender realization is discussed more later on.

Phase 2: EFR price

EFR prices are simulated on two levels: five-year average and yearly bid. The simulations and calculations are carried out in euros. Since there is no available price time series or reliable forecasts, five-year average prices are simulated based on optimistic, realistic and pessimistic views. The views are combined in probability distribution by using triangular distribution, where lower boundary, mode, and upper boundary represent the views respectively. For base simulations, lower boundary is set to the lowest accepted price in 2016 EFR tender (8.12 €/MW/h), mode to the average of accepted bids (10.95 €/MW/h) and upper boundary to a five-year realized average in German PCR market (18.56 €/MW/h). The lower end is set so low due to very intense competitive outlook on market. The average is regarded as the most probable outcome in the future and thus it is chosen as a mode. On the other hand, it is seen unlike that the prices would increase above German level from already low levels and thus the maximum limit. Uniform distribution is rejected due to a relatively wide price spread, which is considered to yield in unnecessary strong revenue fluctuation in MCSs. Simulated prices with above parameters are illustrated in figure 35.

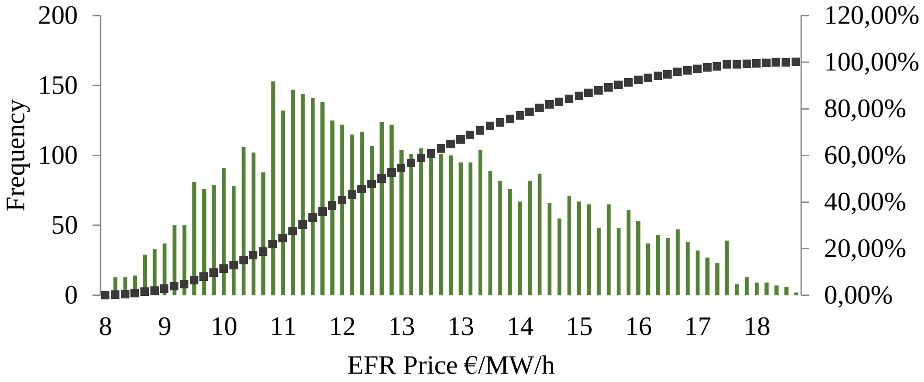


Figure 35. Simulation results from 5000 iterations for five year average EFR price with cumulative development for the UK.

Annual prices are derived from lognormal distribution as in Germany. Log normality is assumed since short and medium term price driving process is fundamentally expected to be comparable to the one in Germany. The estimated lognormal distribution provides a scaling factor, but the yearly price is calculated as a product of the five-year average and the scaling parameter. Estimated parameters are derived from the ones used in the case of German half-year prices with downwards adjustment as the time resolution is longer in the UK. Estimated distribution is LOGN [-0,01109; 0,11] and simulated annual prices with 2016 EFR average price are illustrated in Figure 36. The figure shows also minimum, maximum and average prices of accepted bids in 2016 tender. The simulations fit well in realization range with the identical average and thus support the parameter estimations.

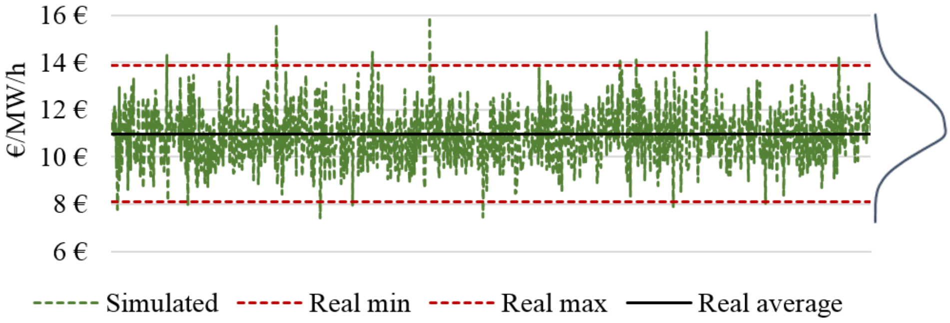


Figure 36. Simulated EFR prices from 1000 iterations and respective density function validated against 2016 realization (real data: National Grid 2016d).

In our MCS the prices are turned to annual revenues by simply multiplying the prices with sold hours. There is an assumption that 10 hours is reserved for annual scheduled maintenance and thus there are 8750 sold hours annually. In addition, looser availability requirements in the UK give some leeway for maintenances. For the same reason, there is no consideration on unavailability costs in the UK simulations.

Phase 3: spot price

The spot prices for the UK are modelled in yearly and weekly levels. Uniform distribution U[46; 56] (€) is applied for yearly spot price. The limits reflect 2013–2016 realization minimum (49,12 €/MWh) and maximum (59,05 €/MWh) with slight downwards adjustment due to decreasing price trend (data: Nord Pool 2017). Whereas, weekly average prices are simulated as in the German model: the distribution of weekly average variation around the annual average is explored and theoretical distributions are tested against the data. The best fit is reached with lognormal distribution LNORM[-0.007597563; 0.111931822] and the results are illustrated in figure 37.

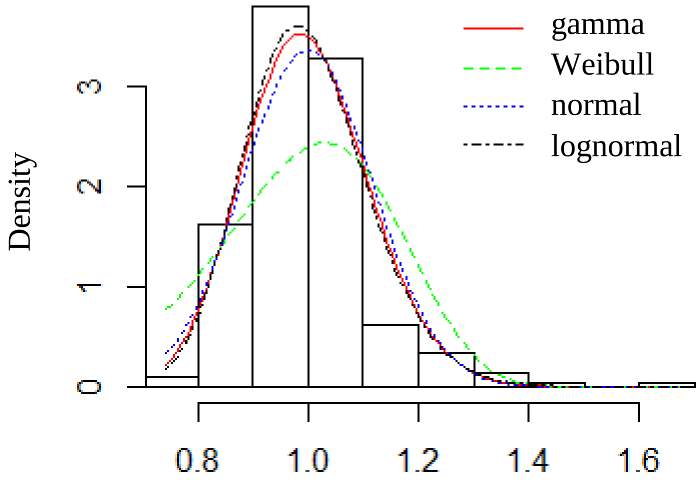


Figure 37. Distribution for the UK's weekly spot price variation around yearly spot average with fitted theoretical density functions (raw data: Nord Pool 2017).

Phase 4: arbitrage revenues

Arbitrage value distribution is estimated by calculating weekly arbitrage values for 1 MW / 1,5 MWh BESS from the 2013–2016 UK spot market data with the algorithm illustrated in figure 31. Similar linear relationship between weekly spot price level and arbitrage value was identified as in the case of Germany. However, in the case of the UK p value for the estimated regression model is well below 0,05 limit and thus the relationship is statistically significant. Nevertheless, the residual spread is relatively large as can be seen in figure 38. Thus, the arbitrage values are modelled from arbitrage ratio (weekly arbitrage value / weekly spot average) distribution as in the case of Germany.

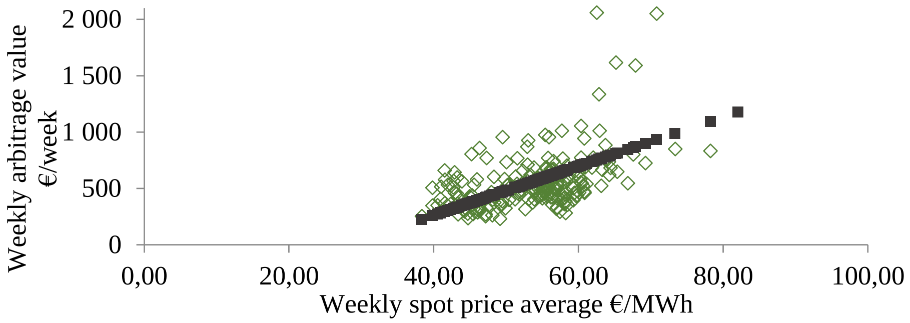


Figure 38. Linear relationship between arbitrage revenues and weekly spot price in the UK. Predicted values as dark dots and observed in green. Large residual spread isy visible as observed values are quite far from predicted ones rejecting linear regression modelling.

Calculated arbitrage ratio and fitted theoretical distributions are illustrated in figure 39. The graph reveal somewhat questionable fit, while lognormal distribution LOGN[2.2727675, 0.3310178] provides the best fit. However, validity is confirmed in cumulative density graph in figure 40. The graph shows that the fit indeed is best with the lognormal distribution and is cumulatively actually relatively good.

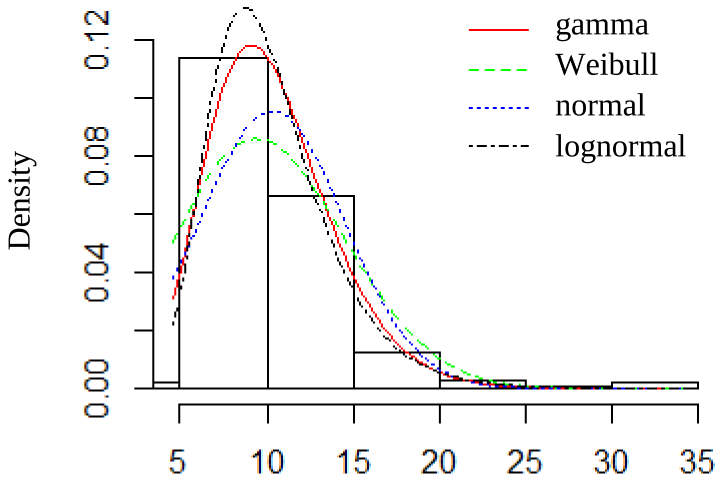


Figure 39. Distribution for arbitrage ratio (weekly arbitrage value / weekly spot average) in the UK (raw data: Nord Pool 2017).

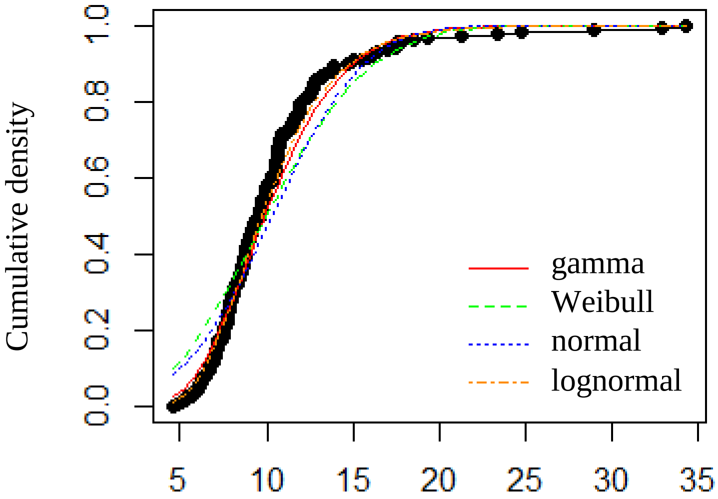


Figure 40.Cumulative density for simulated weekly arbitrage ratio (weekly arbitrage value / weekly spot average) with fitted distributions in the UK (raw data: Nord Pool 2017)

Phase 5: capacity market revenues

Capacity market (CM) is a revenue stacking opportunity that will be further discussed later in section 5.2.2. Nevertheless, it is a valuable opportunity for enhancing financial performance through BESS lifetime. The basic principle is that assets accepted in CM receive fixed payment for maintaining the generation capacity for the TSO's possible use in extreme situations.

CM price has been fluctuating between 24.07–27.55 €/kW/year without significant trend in 2014–2016 (data: National Grid 2016c). Thus, the price is modelled plainly from uniform distribution U[24,07; 27,55] €/kW/year. Probability for getting an agreement in any year is estimated to be 25 % since that is the percentage of BESS in 2016 auction that was accepted (500 MW / 2000 MW). Potentially achieved CM agreement in any year is expected to continue until the end of BESS life time. This is assumed due to realized long agreements granted for BESSs. However, since the auctions are held four years before the commitment period, the first four years are excluded from CM revenue option.

Phase 6: Model validation

Prevailing model is tested and validated with a random simulation output analysis. As earlier, the validation is carried out with revenue and cost structure analysis together with free cash flow analysis. Cost and revenue structures with respective free cash flows for one 15-year horizon are illustrated in figure 41. As visible, on revenue side EFR revenues are dominating and show reasonable levels. On the other hand, annual market and relatively low success rate are visible during four years when BESS is not successful in EFR and is operating in arbitrage. Arbitrage revenues are also realizing in reasonable level around 26 k€/MW/year being significantly lower than EFR. In addition, CM revenues are visible with appropriate volume. Revenue/cost ratio represent also a relevant pattern. As such, random simulation results support the model well.

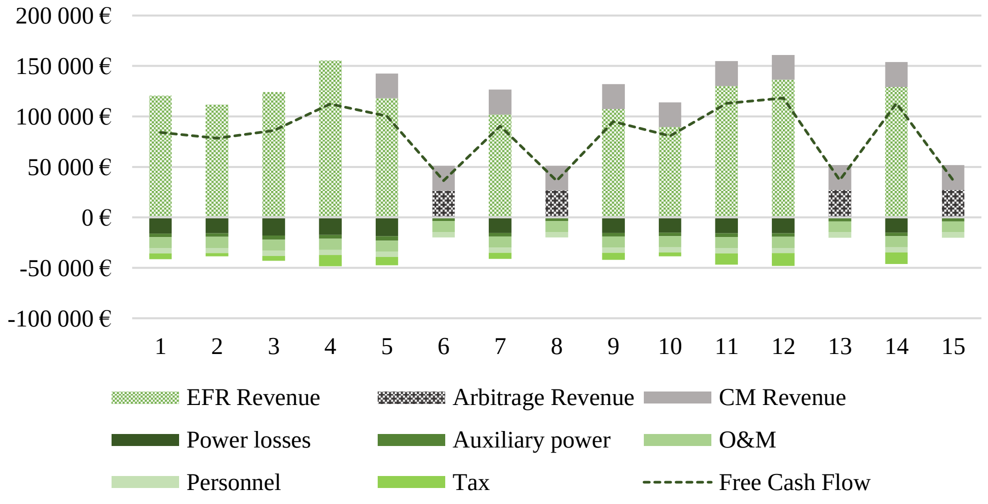


Figure 41. Cost and revenue structure (per MW) for the UK with respective free cash flow for 15 years for one random simulation.

Notable is that the outputs from the UK model vary much more than in German model. The variation is visible in figure 42 with 50 free cash flow simulations revealing the three revenue levels. The levels are EFR and arbitrage revenues with and without CM revenues. However, the variation range reflects the reality, since the UK incurs significantly higher uncertainties, and is regarded relevant. As such, the UK model provides sufficient and reliable outputs for further analysis. Thus, the model is validated and MCSs are performed with introduced parameters.

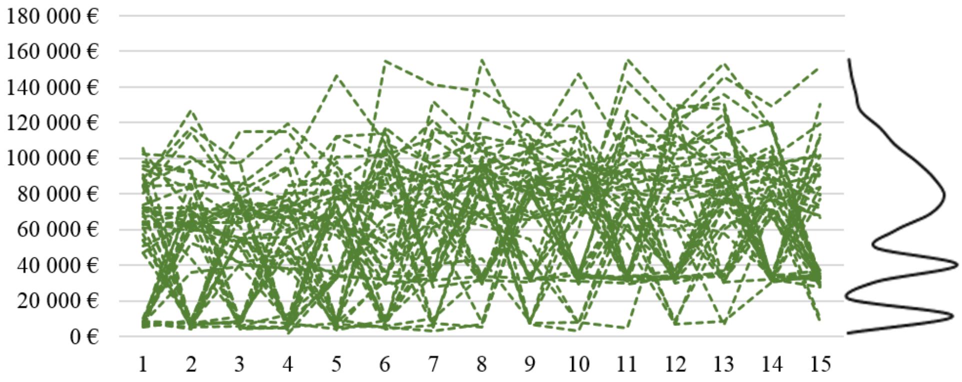


Figure 42. Annual free cash flows (per MW) with 50 iterations and respective density function for the UK. The lowest value peak represents arbitrage without CM, the second peak is arbitrage with CM and the last one includes EFR with and without CM revenues.

4.3.4 Valuation assumptions

Investment evaluations are built on assumptions of future by nature. This is the case also for applied distributions. In addition, in order to calculate output values, some additional assumptions are necessary. They are summarized in table 15 and further commented below. Both countries are simulated with identical assumptions if not stated otherwise.

Table 15. Summary of assumptions used for MCS in case of both Germany and the UK.

1.	NPV Discount rate	6 %
2.	Current BESS investment cost	450 €/kW, 440 €/kWh
3.	Balance of plant costs	120 €/kW
4.	Auxiliary power	75 MWh/year/MWh
5.	Power loss, 90 % round trip efficiency	0.90 MWh/day
6.	Unavailability	3 %
7.	O&M costs	11000 €/year/MWh
8.	Personnel costs	5200 €/year
9.	Corporate tax	30 % DE, 19 % UK

1. Relatively low real discount rate of 6 % is used due to current low interest rates, which are expected to continue for years, and due to inflation ignorance. In addition, questionable financial performance combined to strong willingness to invest in BESSs imply that the industry currently in general uses low rates for the technology.
2. & 3. Current investment costs are based on cost review in section 3.2.1.
4. Auxiliary power stands for internal BESS consumption, which is mainly a result of operating battery cell cooling, heating and controlling systems. The annual figure is estimated based on estimation of average power need around 8.6 kW per MWh capacity, which is regarded as a relevant figure based on empirical experience.
5. Power losses result from energy inefficiencies within BESS. 0,90 MW/day is applied when operating in frequency regulation whilst the cost of losses in arbitrage is included already in arbitrage revenues. 0,90 MW/day per MW is based on technical simulations by Saulny (2017). The cost is assumed due to long term expectation of symmetrical regulation volumes, which leads to a need to compensate energy losses.

6. Relatively low service unavailability of 3 % is assumed due to available well-developed controlling systems and allowed asset pooling. In addition, technology itself is relatively reliable and maintenances can be scheduled effectively.
7. O&M costs are high level estimations based on empirical experience.
8. Personnel costs are estimated based on assumption of two hours of required weekly operating and trading personnel time with 50 € / h cost.
9. Only corporate taxes are taken into account since energy related taxes and levies are exposed to uncertain and developing regulation. In addition, cost quantification would require technical simulations in order to determine generation/consumption patterns. BESS may also be embedded in existing power plants, which potentially frees the unit from consumption taxes. As such, the taxation approach here is rather optimistic.

Auxiliary power, power losses and unavailability costs are valuated based on simulated weekly spot prices. Investment cost, O&M and personnel costs have fixed effect on outputs whilst discount rate and corporate taxes have a relative effect by nature. Corporate taxes are used to calculate free cash flow for profitability calculations. Free cash flows (FCF) here are calculated as EBIT*(1-tax rate) + depreciation. Investment depreciation is calculated as straight-line depreciation.

The simulations and valuations are performed for small 1MW BESS. Applied energy capacities are 1,5 MWh (DE) and 1 MWh (UK). The small size allows assuming price taker role and negligible dynamic price effects on market. These c -rates are based on current installed capacity on the markets and thus makes the results comparable in general and scalable for larger BESSs with identical c -rates of 0,67 (Germany) and 1 (UK). However, it is to be noted here, that the c-rate for actual EFR units in the UK is unknown since no figures have been published yet.

4.3.5 Simulation limitations

The most significant limitation in models is linked to fundamental choice of modeling market operations rather than BESS operations. In our chosen markets BESSs are operating based on system frequency and thus the frequency determines actual BESS operations. In our case, this means ignoring technical constraints. For instance, frequency determines the charging cycles which determine actual life time of the battery. In addition, deterministic simulations from the frequency data would provide information on generation/consumption patterns, which would enable evaluating possible energy taxation effects and unavailability costs more in depth.

On the other hand, combining deterministic operational simulations with stochastic market simulations would be interesting but also somewhat irrelevant. In fact, the deterministic simulations would provide uncertain results anyway as the simulations would be carried out under uncertain markets. This allows simulating straight the stochastic financial effects of the technical aspects instead of the actual operations. Thus, taking into account the nature of the study the chosen approach is well supported.

However, the chosen market approach has its limitations as well. By using probability distributions for modeling, there is no chronology in the data. In addition, there is no information of the future distributions. Indeed, in general, market prices are modelled as time series but since our target is to valuate and estimate investment performance through the whole 15-year investment horizon, the model includes summarizing weekly values to yearly values and further summarizing yearly values to investment case specific 15 year values. Composing the information dilutes effectively time-dependencies in data, making the case specific results and output distributions mostly dependent on average levels and deviations around the average. Furthermore, lack of historical data, especially for the UK, forces the researcher to use relatively high level estimations. Hence, modelling complex and detailed time-series, e.g. regime switching model for spot price, wouldn’t provide sufficient extra value for the research. This supports the researcher’s choice to model the uncertainties from static distributions. The approach still does not ignore long term average price paths, which are included in the models as five year averages.

5 INVESTMENT POTENTIAL EVALUATION

Market analysis findings and hierarchical market evaluations are represented in this section. Each market is discussed and analyzed separately under each investment potential criterion. Finally, hierarchical AHP evaluations are derived for each criterion and composed to overall AHP evaluation. Evaluated issues and information is made available for reader in order to increase the transparency in subjective AHP rankings. To put the analysis in context the following provides short country specific background information.

Germany

German markets have been characterized as the most developed markets in Europe for deploying energy storages (German Trade and Invest 2016). The statement gets support from the wide range of reference installations and constant development in the industry sector. The market has been in focus of ES sector especially due to the country’s fundamental energy transition towards renewable energy sources (Energiewende), well-functioning markets and favorable policies and subsidies.

Large scale BESS penetration to German market started in 2014. This is when the first European commercial battery storage system was launched in the country (German Trade & Invest 2016). Since that, numerous commercial and R&D projects have been integrated in German grid and started operating in PCR market. The overall increase of ES capacity is likely to continue also in the future, whilst business models are still shaping.

The United Kingdom

The balancing mechanism and markets in the UK are more complex compared to the ones in Germany. The electricity market itself is mature, but is also under significant changes while the increase of RES, the security of supply and the energy cost minimization are the driving forces. These developments have attracted interests and investments in ESs and more specifically BESS sector in the UK.

However, the sector is new in the UK as the main revenue source, EFR, for the technology is not even operational yet. Thus, the market includes relatively high amount of uncertainties reflecting the risk level in the market. A complete wild card is also the UK's approaching EU exit. Despite the challenges, ESs are expected to have an integral role in the UK's power system in a long term (Allan, Wilson, McGregor & Hall 2010: 4105). However, the business models in general are evolving also in the UK. Indeed, complexity of potential ES revenue streams are underlined as one of the main barrier for deploying ESs in the UK (Energy and Climate Change Committee 2016).

5.1 Market scheme suitability

The chosen markets are differing a lot structurally and principally and thus naturally represent very different business making environment. This framework and its suitability for BESS market participation are critical factors in decision making as they determine largely how the market participants make business and how cash flows are generated. The following market scheme suitability analysis is largely based on the market principles discussed in chapter 2. The principles and characteristics are summarized in table 16.

Table 16. Summary of German PCR and the UK's EFR market characteristics.

	Germany	**the UK**
Market principle	Joint tender	Tender
Period	1 Week	4 Years
Payment based on	Capacity only	Capacity only
Payment amount	Pay-as-bid	Pay-as-bid
Bid range	1–150 MW	1–50 MW
Pooling allowed	Yes	Yes
Availability requirement	100 %	95 %
Unavailability penalty	Proportional	Proportional

5.1.1 Suitability analysis

Germany

German joint weekly PCR tenders with neighboring countries offer frequent and thus flexible entry interval. The system is well-functioning with its transparent Regelleistung.net online market platform. There is already a relatively long history providing certainty and predictability for future cash flows. The scheme indeed provides simple cash flow generating principle through predetermined pay-as-bid capacity payments. Pay-as-bid system also allows applying different bidding strategies enabling some leeway around the average prices. This fact indeed gives a change to gain above average prices with successful bidding. The prices may be gained with wide range of installations due to minimum bidding size of 1 MW and very flexible pooling policies.

There are still some drawbacks, too. Weekly tender period is still somewhat long in case a bid is not accepted: failing in bidding process might result in unacceptably low utilization rates especially in case of frequent bid overpricing. Furthermore, availability requirement and penalty policies are very strict in Germany compared to the UK. In case the unavailability occurs once, the received bidding price is diminished proportionally to a time period and the amount of frequency controlling not delivered (Consentec 2012: 14). Nevertheless, the proportional penalty cannot be used as a buffer: in frequent cases, TSO holds privilege to impose penalty of ten times this diminished amount and to invalidate pre-qualification required for bidding (Consentec 2012: 14). The policy limits standalone installations as ensuring the availability, by controlling state of charge, while being in service is problematic. Embedding BESS in existing power portfolio reduces the problems by providing back up capacity and flexible charging power. Thus, for new market entrants, close collaboration with another utility company might be needed.

As such, German PCR market is well structured with robust reimbursement logic. As an international market, it offers effectively access to large tendering volumes. In addition, flexible pooling policies enable market participation with a wide range of assets.

Drawback in the German market scheme is the strict availability policies, which increase BESS investment costs via relatively large energy capacity preference.

The UK

British scheme is more or less comparable to the German one, but it does not have a comparable history. However, current EFR scheme in the UK as a tendering for fixed period with only capacity payments based on pay-as-bid principle follows the basic characteristics of German market. It provides systematic and transparent framework with clearly determined payment logic. Availability requirement and unavailability policies are more suitable in for BESS in the UK: 95 % service requirement is realistic. In addition, there is no strict treatment in frequent unavailability as the proportional penalties are applied in any case. The fact helps especially standalone application operations, but may reduce also investment costs via smaller needed energy capacity meaning higher c-rate. Nonetheless, the TSO does not allow using the policy for offering another services affecting actual EFR delivery (National Grid 2016f: 9).

In contrast to Germany, there are some significant distinctive concerns and entry barriers arising from future commercial viability that can be divided in two categories:

1. Uncertainty on future market scheme
   Currently there is no decided EFR market scheme for the future. However, the TSO assumes the market to be tender based (National Grid 2016f: 14). In addition, annual tenders for long term contracts and monthly ones for short term contracting are anticipated by the TSO (National Grid 2016f: 21). This gives positive outlook for future and reduces risk related to the second point.
2. EFR contracting time span
   The span is long with four year contracting but not long enough to provide financial security over BESS lifetime. This also reflects the uncertainty after potentially successful bidding: what are the changes to win a contract in future tendering and what are the alternative revenues in case of not getting accepted in EFR. Thus, the current period incurs significant risks.

5.1.2 Hierarchy evaluation

German market scheme is evaluated to have moderate to strong advantages over the UK. Even though the UK has an advantage in terms of availability policy, the issue does not change the big picture: the UK lacks a determined future market scheme with predictability and revenue certainty. Evaluation quantification is represented in table 17.

Table 17. AHP Matrix: market scheme suitability. Column w shows the local priorities.

	DE	UK	w
DE	1	4	0,80
UK	0,25	1	0,20

5.2 Cash flow generating potential

Cash flow generating potential is analyzed and evaluated through frequency regulation price level and revenue stacking possibilities. Annual and discounted cash flows per 1 MW for both markets are then derived for 15 years period with 6 % discount rate. The analysis vary relatively much as the timespan for available data is very different.

5.2.1 Price level analysis

Germany

Although pay-as-bid market allows speculating with different bidding strategies, the generated cash flows in long term are naturally highly dependent on average price level. Weekly PCR market price in joint tenders averaged around 2500 €/MW in 2016. Long term 2008–2016 yearly averages have been fluctuating around average of 3300 €/MW with a slight decreasing trend. The trend is concerning as recent 2017 tenders anticipate the long term decrease to continue. Annual averages for 2008–2017 are illustrated in figure 43. 2017 Numbers include ten first weeks of the year. (Data: Regelleistung.net 2017f.)

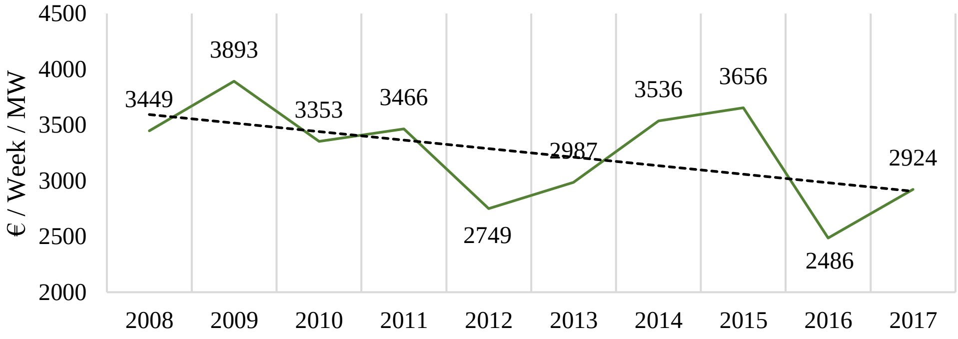


Figure 43. Average PCR weekly price (€/MW) in joint auctions with dotted trend line (data: Regelleistung.net 2017f).

However, the annual averages do not reveal realized relatively high volatility of 10,24 %. Volatility is defined as magnitude of price variations and calculated as standard deviation of logarithmic returns. Volatile auction results are represented as hourly prices in figure 44. The figure 44 illustrates also trends over long and short term. Long term trend is captured by linear approximation, whilst short term trend is calculated as moving average for rolling half-year periods. There is also a recurrent price increase during summers and spikes in turn of the year. The seasonality effect is illustrated in figure 45.

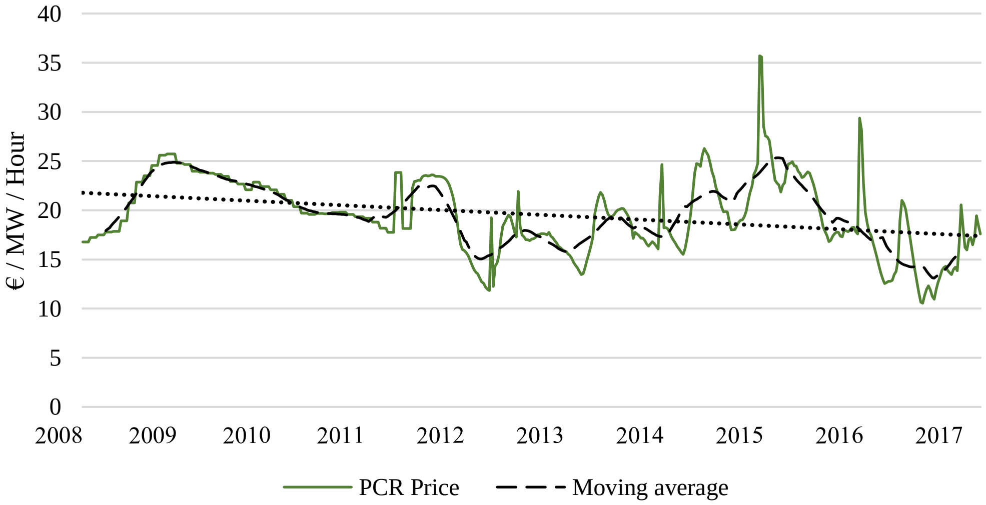


Figure 44. German joint auction PCR price development 2008–2016 (2017 first ten weeks) (raw data: Regelleistung.net 2017f).

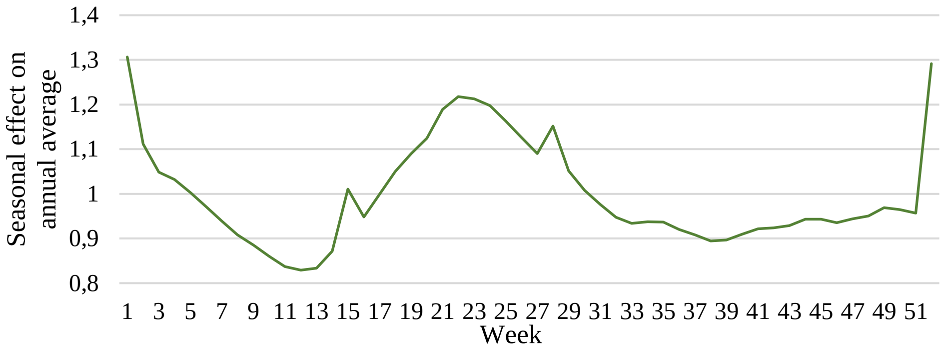


Figure 45. 2012 - 2016 Average weekly PCR price seasonality during 2012–2016 in relation to yearly averages (value 1) (raw data: Regelleistung.net 2017f).

As such, the market offers somewhat potential price level, but with volatile prices. Price fluctuation is not relatively strong only between weeks, but also during half-year periods and annual averages. Also the price spread among the weeks has been varying much as discussed in section 4.3.2. However, some of the volatility is explained by a strong seasonal pattern, which also enables more effective price forecasting. Nevertheless, discounted cash flows (15 years, 6 % rate) result in NPV of 1250 €/kW with 2016 prices and 1850 €/kW with 2016 prices. Respective annual cash flows are 130 and 190 €/kW. As such, the cash flow generating potential in PCR market indicates somewhat sufficient levels, but price development and volatility are reflecting some disquieting downside. It is well founded to assume that decreasing price trend continues moderately also in future as the competition tightens. The competition issue is further discussed in section 5.4.2.

The UK

Pay-as-bid system allows relatively large spread also in the UK and thus different financial performance among the EFR providers. Indeed, in the first EFR auction in 2016 the lowest accepted price was over 40 % smaller than the highest one with price spread of 8,12–13,89 €/MW/h (7,00–11,97 £/MW/h) (data: National Grid 2016d). Weighted average price for the accepted bids was 10,95 €/MW/h (9,44 £/MW/h). As such, the hourly prices are significantly lower than the ones in German auctions in general.

In fact, in the initial auction most of the investors valuated their BESS projects clearly higher than the realized prices. The accepted bids were from the very beginning of the price distribution, while the most frequent bidding price and weighted average was around 23 €/MW/h (20 £/MW/h). Thus, the distribution does not indicate strong support for profit generation potential with the realized price level. Potentially the winning bids were significantly riskier positions with a strong willingness to be first in the market. The realized bidding price distribution is illustrated in figure 46.

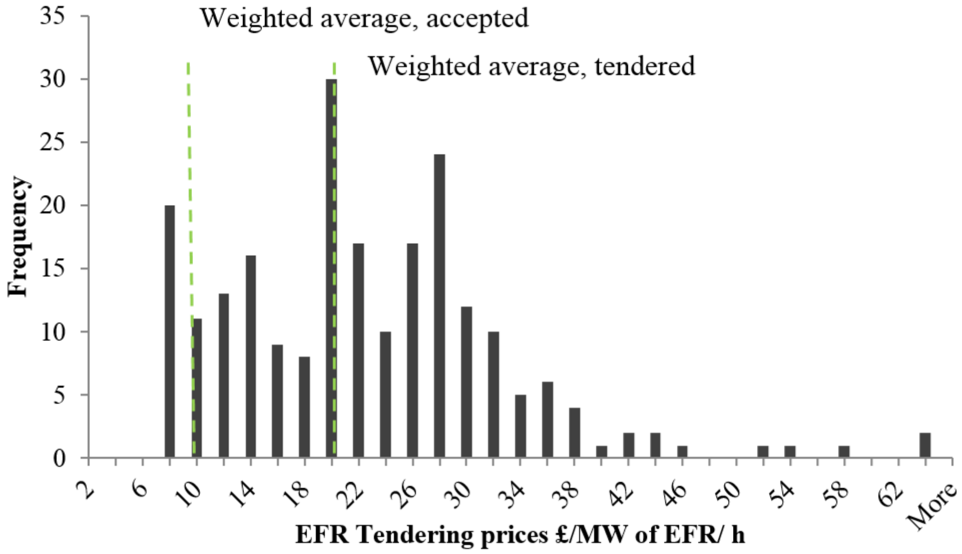


Figure 46. 2016 EFR Tendering price (£) distribution of all bids (data: National Grid 2016d).

Actual annual and discounted cash flows for three different price scenarios derived from accepted EFR bids are illustrated in figure 47. The scenarios are based on the average (10,95 €/MW), highest (13,89 €/MW) and lowest (8,12 €/MW) prices among the accepted bids. The annual cash flows with the range of 71–122 €/kW yielding in NPVs of 690–1200 €/kW. The figures are significantly lower than the ones in Germany and thus signal from very challenging financial conditions for the units if operated only with EFR revenues.

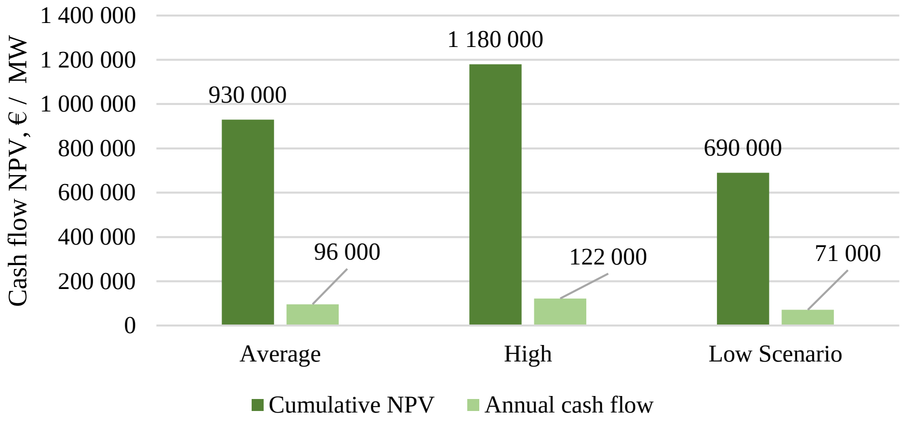


Figure 47. Net present value (15 years, 6 %) of cumulative and annual cash flows from EFR market with the average, the highest and the lowest accepted prices in 2016 tender.

The price level in coming EFR tenders is a concern in the UK. It might be hard to lift the price closer to German prices as the competition seems fierce (see section 5.4.2) and the initial price is already so low. Thus, it is expected that the prices in the UK remain low at least in near and medium term substantially decreasing the investment potential.

5.2.2 Revenue stacking opportunities

Currently there are no relevant revenue stacking opportunities simultaneously with PCR in the German market. This is especially due to 100 % availability requirement. Furthermore, Germany in general pushes power markets towards transparent and undisrupted price formation. For instance, capacity reserves are not allowed to operate in electricity markets (Federal Ministry for Economic Affairs and Energy 2017c). Such attitude and regulation imply that stacking might be difficult in Germany also in future.

In contrast to Germany, there is a simultaneous revenue stacking opportunity from capacity market (CM) in the UK. The CM revenues are stackable with actual revenues from energy and ancillary service markets (Department for Business, Energy & Industrial Strategy 2016). CM covers both generation and demand side assets procured for back-up capacity in order to ensure supply security. The procured capacity is auctioned yearly and payments are paid for maintained capacity. CM auctions have been organized annually since 2014 whilst BESSs made their breakthrough in 2016 with 500 MW of new contracted capacity for 12–15 years starting in 2020/2021 (data: National Grid 2016c). In total, there were around 2000 MW of bid BESS capacity in 2016 (National Grid 2016c).

In 2016 CM auction (delivery starting 2020/21) BESSs were rewarded with around 500 MW capacity and with yearly clearing price of 26,1 €/kW (22,5 £/kW) (National Grid 2016c). Thus, additional yearly gross income would be 26 100 €/MW (22 500 £/MW) and give significant increase in cash flows. Indeed, CM revenues result in 18–27 % share of total revenues with different EFR prices. NPVs are illustrated in figure 48.

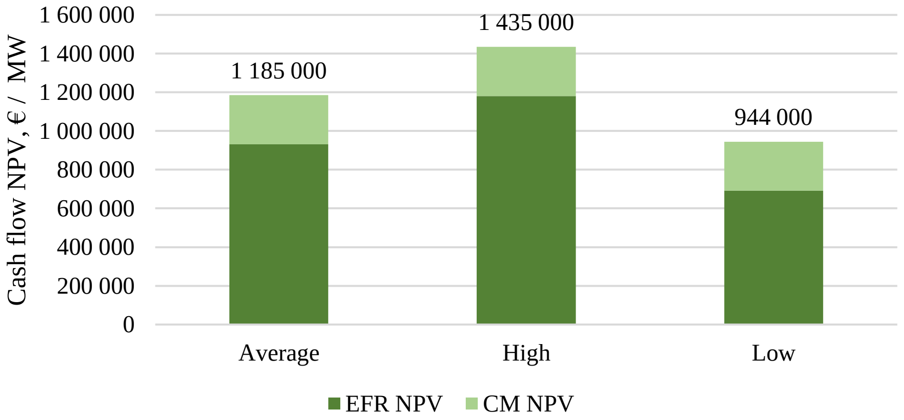


Figure 48. Discounted (15 years, 6 %) total cash flows from the UK's EFR and CM market with the average, the highest and the lowest accepted prices in 2016 EFR tender and achieved price in 2016 CM tender.

Another stacking opportunity specifically in the UK, although very speculative, comes from triad revenues. They are revenues from an incentive system to reduce load in transmission grid in peak hours through winter. However, for BESS serving in EFR these are very speculative revenues as they would require net power output in distribution network during the triad periods. Assuming the revenues would be naïve as in/output power is determined by the system frequency. Thus, the triads might result in costs as well. Furthermore, the regulatory authority has proposed a removal of the incentive from embedded generators (i.e. the status for ES connected to distribution grid) (Ofgem 2016).

5.2.3 Hierarchy evaluation

All in all, the cash flow generating potential solely from EFR in the UK is significantly less than in Germany's PCR market. On the other hand, more multifaceted market provides valuable revenue stacking opportunity in the UK. However, these additional revenues come with great uncertainties, are incremental by nature and thus provide very limited revenues exploited solely. Thus, the UK market can be stated relatively unattractive and less potential than Germany's from cash flow point of view. Price level and revenue staking AHP comparison matrices are in table 18 and 19 respectively.

Table 18. AHP Matrix: price level. Column w shows the local priorities.

	DE	UK	w
DE	1	7	0,88
UK	0,14	1	0,13

Table 19. AHP Matrix: revenue stacking opportunities. Column w shows the local priorities.

	DE	UK	w
DE	1	0,125	0,11
UK	8,00	1	0,89

5.3 Regulation and support policies

Regulatory framework plays naturally a significant role in both markets. However, despite the attention ESs have gained, regulation is surprisingly immature in general. Not only in the chosen countries but also in EU level. The following elaborates the most relevant regulation and support policy issues country specifically under three criteria.

5.3.1 Regulation suitability

Germany

German plays a significant role in EU's energy policy development and respectively EU policies have a significant impact on the German markets. EU's energy market legislation itself is a large regulatory whole. However, EU-level legislation, specifically electricity directive 2009/72/EC, does not recognize ESs activities or assets. This usually results in treating ESs as generators within EU (Papapetrou, Maidonis, Garde & Garcia 2013: 14). There is no national recognition for ESs as their own asset class in German legislation either. However, Germany has taken somewhat differing approach from general EU approach: ESs are treated both as generation and consumption assets. Within the balancing system framework, the treatment is based on every 15 minute balancing period based on realized consumption and generation pattern (Bundesnetzagentur 2017).

As a result, there is applied regulation, but ES business itself is unregulated. Furthermore, various ES projects have paved the way as there are established practices and consistent policy treatments for ESs in the country. However, treatment as consumer exposes ESs to related taxes and payments. Besides consumer side taxes, there are no other considerable regulatory challenges (Norton Rose Fulbright 2017). Regulatory development and clarification can still be expected in future in Germany. Indeed, it still has been pointed out that also in Germany the regulatory framework is somewhat immature for ESs and is constantly developed (Norton Rose Fulbright 2017).

The UK

There is no specific regulation concerning or identifying ESs currently in the UK either. However, in the UK ESs are regulated mainly as a generation asset (Department for Energy & Climate Change (DECC) 2016: 11). Generators in general need to hold generating license. Nevertheless, small generation units do not need to hold generation license if its power output to the grid is

1. less than 10 MW; or

2. less than 50 MW in case of unit with less than 100 MW of declared capacity (The Electricity order 2001 No 3270).

Thus, most BESS applications are exempted from the related costs and obligations. On the other hand, the license obligation is limiting large scale ES projects effectively to 50 MW. It is still notable that there is a lot of regulatory unclarity as the regulation is currently being reviewed (DECC 2017: 3). In addition, despite the generator status ESs face significant tax disadvantages as further discussed later. In fact, non-existing regulation and related unestablished practices are a major disadvantage as the profitability predictability faces significant uncertainties and game changing developments may penalize early investors unreasonably. However, the regulator and governmental Department of Business, Energy and Industrial Strategy are regarded supportive towards ESs giving optimistic signals for future regulation (Hassan & Dalton 2016).

5.3.2 Tax and payment obligations

Germany

Since ESs are regarded also as consumers, they are exposed to related taxes and payment obligations for charged energy. The problem is recognized by authorities and is taken into account by applying exemptions for ESs. Electricity taxation and payments in Germany for consumers is high in general. In 2016 the highest taxation for industrial electricity consumers in Europe was indeed in Germany, where non-recoverable taxes and levies summarized approximately half of total electricity price (Eurostat 2016). According to Eurostat (2015: 19–20), the additional taxes and payments for industrial end-users are:

1. Concession fee (I.e. levy for financing rights to install and operate mains)
2. Levy for renewables (EEG-Umlage i.e. reallocation fee for financing RES)
3. Levy for combined heat and power (KWKG-Umlage)
4. Levy for financing grid fee reductions (§19 StromNEV-Umlage)
5. Compensation fee for offshore wind farms (Offshore-Haftungsumlage)
6. Levy for demand side management financing (Umlage f. abschaltbare Lasten)
7. Electricity tax.

Major costs result from levy for renewables, electricity tax and concession levy, which account for around 20 %, 8 % and 5 % respectively with slight yearly changes (Zeh, Müller, Naumann, Hesse, Jossen & Witzmann 2016: 5). In addition, there is a grid fee that accounts for about 20 % of the total electricity price. Nevertheless, under the German law (EnWG 2012, Article 118), ESs are freed from the grid fee, including all pegged taxes and fees (Zeh et al. 2016: 5).

There are other exemptions too resulting in reduced obligations. Renewable Energy Source Act (EEG, Article 60) ensures that ESs are exempted from levy for renewables (Zeh, et al. 2016: 5). Furthermore, if electricity only from RES is charged and discharged by grid connected ES, the unit is exempt from electricity tax (StromStG, Article 9 Abs. 1 Nr.1). This issue is solvable with guarantee of origins for renewables. There is also proceeding proposal for including ESs in electricity tax regulation so that they would enjoy tax exemption as regular generator (Janzen & Wippich 2017). Thus, ESs are exempted from major electricity consumption related taxes and payment obligations except the concession fee. However, taking into account the exemptions total tax charges yield in around 6,54 € / MWh of consumed electricity in 2017 and fluctuates between 2–10 €/MWh in general (data: Bundesverband der Energie- und Wasserwirtschaft 2017).

The UK

Since, ESs are recognized as generation, electricity tax is not imposed in the UK. However, there are several environmental programmes affecting ESs in the UK. Furthermore, due to the unclear regulatory situation ESs are currently facing costs from both the generation and the consumption sides - even the generator status does not prevent the costs (Hassan & Dalton 2016). The relevant issues and effects are compiled below.

1. Climate Change Levy (CCL)

CCL is a tax charged for energy delivered to non-domestic energy end user. The tax amount for electricity in 2017 is 5,68 £/MWh (6.58 €) (Government of the UK 2016). Even though ESs are regulated as a generation, they are regarded end users during charging. Nevertheless, notice CCL 1/3 (section 10) (Government of the UK 2017b) exempts BESS from main CCL rates for electricity not taken for fuel purposes. Tax authorities have also given CCL exemptions for individual projects (Hassan & Dalton 2016). Thus, eventual CCL cost is uncertain with promising exemptions.

2. Renewables obligation (RO)

RO scheme supports large scale RES by imposing obligations on electricity suppliers. The suppliers are obliged to have certain amount of RO certificates for each delivered MWh. The costs of the obligations are collected from electricity consumers. Cost for RO certificate has been increasing and in 2017/18 it is substantial 18,64 £/MWh (21,60 €) (Ofgem 2017c). However, the actual amount depends on generation portfolio of the electricity supplier. In addition, the system will be diminishing as it will eventually be replaced by Contracts for Differences.

3. Contract for Difference (CfD)

CfDs are private contracts between the government owned Low Carbon Contracts Company and low carbon electricity generator (Government of the UK 2017a). The CfDs are a hedging possibility for the generators to fix their income on price strike level: the price difference between realized prices and the strike level is paid by the government's company (Government of the UK 2017a). The CfD costs are paid by consumers and are dependent on future price levels. The cost is estimated to be several pounds per MWh.

4. Feed-in Tariff (FiT)

FiT scheme supports small scale RES production by ensuring reimbursement for domestic electricity producers. The payments are made by the licensed electricity suppliers and the costs are collected from electricity consumers. The cost was around 3 £/MWh (~3,5 €) in 2016 (data: Ofgem 2017d).

In addition to the above ones, confusing treatment as a generator while charged as consumer may result in double-charging in network charges (Hassan & Dalton 2016). Thus, the taxes and cost obligations are a major concern in the UK for ESs currently. They are also considerably higher than in Germany with level around 10–20 €/MWh.

5.3.3 Subsidies and financing

Germany

There are no straight subsidies for ESs in Germany currently. However, there is a national ES funding programme, Energy Storage Funding Initiative, provided by the German Federal Government in order to allocate funding for development of ES systems (Federal Ministry for Economic Affairs and Energy 2017a). Since 2012, around 200 M€ has been allocated to around 250 projects ranging from residential storages to megawatt scale grid applications (Federal Ministry for Economic Affairs and Energy 2017a). This explains for one's part the rapid expansion of ES capacity in Germany in recent years. The program is full in present, but funding after the initiative is expected to continue under the government (Federal Ministry for Economic Affairs and Energy 2017a). Thus, the German support policies cover a wide range of ES applications. However, the policy is research driven and does not provide funding for ESs without a development focus.

German government owned development bank KfW has also energy related financing programmes covering ES development. Currently, there is an ongoing 30 M€ funding programme supporting decentralized battery ES systems integrated with photovoltaic installations (Federal Ministry for Economic Affairs and Energy 2017a). Furthermore, the bank offers financing for projects supporting German energy transition in general.

The UK

There are currently no straight subsidies or financial support policies in the UK either. ES specific subsidies in future are also unlike (Hassan & Dalton 2016). This underlines the UK's willingness to develop ES sector purely as a market driven solution.

However, there has been a significant public funding for innovations and R&D project for ESs through Low Carbon Network Fund (Ofgem 2017b). Currently there is no such an opportunity in sight. Besides the governmental aid, e.g. the Research Council UK (RCUK) has supported ES R&D projects (RCUK 2017). This financing opportunity is expected to continue also in future, but solely for research projects.

5.3.4 Hierarchy evaluation

While both countries have more or less confusing generator/consumer -treatment policies, the situation is clearer and more determined in Germany. Regulatory development in the UK is urgent and the problem is recognized: a new asset class for ESs has been proposed by The Energy and Climate Change Committee to solve unclarity issues (2016). In Germany there are no major signs that the attitude or developing ES regulation would change the role or financial performance significantly in near future. Comparison matrix for regulation suitability is in table 20.

Table 20. AHP Matrix: regulation suitability. Column w shows the local priorities.

	DE	UK	w
DE	1	3	0,75
UK	0,33	1	0,25

While both countries expose significant tax and payment obligations for ESs, Germany has a clear advantage with its more favorable exemptions. Rough estimate shows that costs per charged MWh in the UK could be more than double compared to Germany. Thus, the UK has clear disadvantage as quantified in table 21. Nevertheless, the situation is likely to change in future as it goes hand in hand with regulatory development.

Table 21. AHP Matrix: tax and payment obligations. Column w shows the local priorities.

	DE	UK	w
DE	1	5	0,83
UK	0,20	1	0,17

From subsidy and financing opportunity perspectives both markets are pretty much equal: there are no straight subsidies and financing aid is applicable only for R&D -projects. Nevertheless, Germany is slightly preferred also here as governmental and regulatory attitude towards ES investments can be seen more favorable in Germany due to funding programmes. This fact provides some optimism for more generous financing conditions for future investments. Comparison matrix for subsidies and financing is in table 22

Table 22. AHP Matrix: subsidies and financing.

	DE	UK	w
DE	1	2	0,67
UK	0,50	1	0,33

5.4 Size and Competition

The chosen markets represent also very different business frameworks in terms of market size, its development and competitive environment. These issues have a strong impact on the investment potential especially in primary frequency regulation as the customers are limited and the deliverable service does not allow diversification.

5.4.1 Size and growth

Primary frequency regulation markets in general are fixed by volume. For instance, total primary control reserve capacity in continental Europe synchronous area is set to 3000 MW (ENTSO-E 2009: 6). The amount is dimensioned to cover sudden disconnections of roughly two very large power plants. Thus, there is no organic growth potential in general.

However, both countries are increasing their RES share of generating portfolio. Even though most of the RES balancing need falls on secondary and especially on tertiary control markets due to longer timescale, increasing intermittent RES generation may also have an impact on the future primary balancing need: RES decreases inertia due to reducing synchronous rotating masses in the power system. Thus they reduce the natural buffer that responds automatically to frequency changes. The volume growth potential from inertia development is incremental, but may have impact in otherwise fixed market.

Germany

German proportion of the continental Europe 3000 MW, i.e. PCR market size, in 2016 was 583 MW. Total market size including joint tendering areas averaged 806 MW in 2016. After mid-January 2017, the area includes also France and thus the total market size jumped to around 1400 MW. As such, the joint tenders represent nearly half of the required reserve capacity in continental Europe. (Data: Regelleistung.net 2017f.)

National German market size has been relatively stable over the past 10 years with minor fluctuation around 600 MW. In relation to the volume size, total market value has faced somewhat decreasing trend driven by the price development. The value has dropped from 2008-2010 average of 120 million euros to 75 million in 2016. The market developments are illustrated in figure 49. (Data: Regelleistung.net 2017f.)

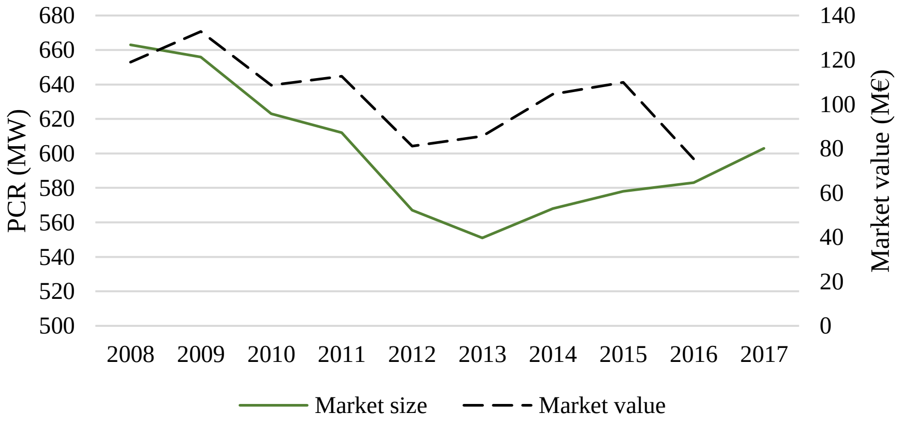


Figure 49. German PCR market size and total value development based on tendered capacities and realized average prices (data: Regelleistung.net 2017f).

German contribution to the whole continental Europe capacity is expected to remain at the same level in future. On the other hand, Denmark is planning to join the joint tendering system expanding the market size and increasing liquidity further (Regelleisgtung.net 2017b). The market coupling would give some space for market and ES capacity growth in PCR market. Nevertheless, no other growth is expected in near or mid future.

The UK

Current EFR market size in the UK is 200 MW as this is the procured capacity in the 2016 tender. With the price realization the market value is around 76 M€ (66 M£) in total for four years. As such, total market is rather small and clearly smaller than in Germany.

In addition to increasing RES, the UK's coal condense plants will be closed by 2025 (DECC 2016a). This development reduces system inertia and traditional frequency response capacity further resulting in greater "organic" growth potential than in Germany. In addition, in 2020–2021 the largest secured generation disconnection is increased to 1400 MW consequently resulting in increasing fast frequency control capacity requirements (National Grid 2016a: 7). In this framework EFR market itself has growth potential. This is also supported by successful first tendering from the system perspective. The TSO has also expressed that it is expecting to see growing EFR demand (National Grid 2016f: 21). Indeed, forecasted EFR volume need is growing over the next 10 years (National Grid 2016f: 14). Nevertheless, absolute volume numbers are not available.

5.4.2 Competitive environment

In volume fixed market capacity increase may result in sudden competition tightening. Such development carries also a risk of critical price impact – especially in case of already volatile and sensitive prices. In addition, installed direct and indirect competition are threats for tendering success and cash flows from substituting revenue streams. The markets represent very different competitive environments as discussed below.

Germany

There are currently reported 287,6 MW of operational, contracted, announced and under construction BESS (> 1 MW) capacity in the joint tendering area (Sandia National Laboratories 2017). From that capacity 179,1 MW is reported to be used for frequency regulation. Germany represents clearly the biggest share with 19 reported PCR units.

As a result, straight ES competition within the tendering area is quite high. In Germany, the reported BESS capacity covers already 26 % of the country's total PCR need. Within the whole tendering the coverage is 13 %. Although ES capacity covers only proportion of the market, it is notable that the capacity has penetrated the market within last few years. Compound Annual Growth Rate (CAGR) 2013–2016 realized in 130 %! The capacities are in table 23 and growth in figure 50. (Data: Regelleistung.net 2017f.)

Table 23. Reported electro-chemical battery energy storage capacity in joint tendering area (data: Sandia National Laboratories 2017).

Country	**Reporter power (MW)**	**Reported units (pcs)**	***PCR (MW)**	**PCR (pcs)**	**Operational ^(MW)**	**Operational (pcs)**
France	14,8	7	6,3	3	12,8	6
Germany	254,8	22	154,8	19	207,8	19
Netherlands	17	3	17	3	17	3
Switzerland	1	1	1	1	1	1
Total	287,6	33	179,1	26	238,6	29

*Reported to be used for frequency control.
^Reported to be operational or contracted to operation.

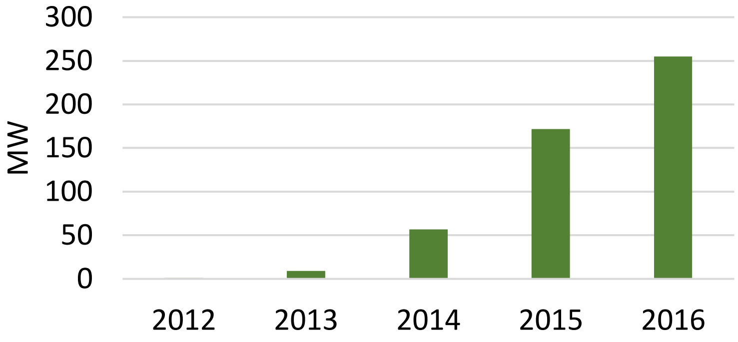


Figure 50.Reported BESS capacity growth (CAGR 2013–2016 130%) in Germany (data: Sandia National Laboratories 2017). (2017 Estimated increase + 50 MW).

In addition to storage units, PCR capacity can be offered technically from most thermal, hydro and pumped hydro stations in Germany (Just 2015: 5). Indeed, all major large electricity generating companies are prequalified for PCR provision (Regelleistung.net

2017e). In total, there are currently 22 companies prequalified only in Germany (Regelleistung.net 2017e). Thus, new BESS capacity is above all substitutive by nature. These issues alongside the fast BESS penetration underlines the tightening competitive environment in Germany. The situation may result in significant price slide supported by decreasing BESS investment costs and low utilization rates of conventional plants as their production is replaced more and more by RES, which drives them to seek other revenues.

The UK

The full EFR capacity is covered by BESSs during the first four-year period. This gives a very competitive set up for coming tenders as well. Thus, even in case of significant EFR market growth, BESSs are likely to play substantial role and face intense competitions in the market in future as well. More straight BESS competition might come through CM. If new BESS assets are awarded also in coming auctions, units with secured CM revenues would have clear competitive advantage in future EFR tendering. Such scenario would support continuum of low EFR price level. Notable is that the 500 MW of accepted BESS capacity in CM auction equals to 2,5 times current EFR market size!

There are seven reported at least 1 MW BESSs in the UK with a total capacity of 43,5 MW (data: Sandia National Laboratories 2017). The reported capacity does not include the 200 MW EFR capacity which will lift the growth figure (CAGR 2013–2017 to 160 %. However, besides the EFR units only three are reported to aim primarily in frequency response services with total capacity of 32 MW. Capacities are illustrated in figure 51.

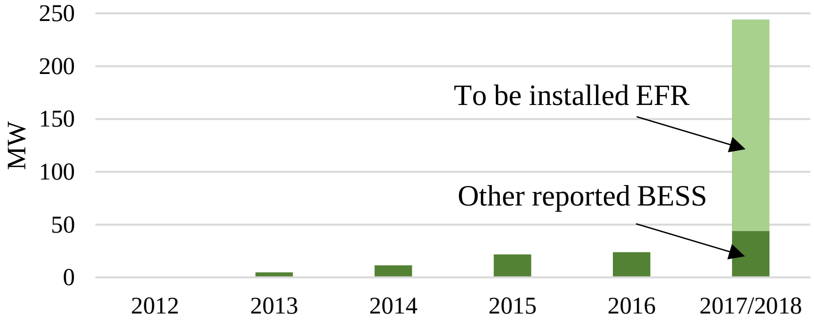


Figure 51. BESS capacity evolution in the UK (data: Sandia National Laboratories 2017).

EFR response time requirement is effectively limiting the applicable technologies. Thus, indirect competition within EFR is likely to remain low. However, there is a significant number of generators available for the primary, secondary and high frequency controlling due to the mandatory capability for providing this service for large generators (=>100 MW). For instance, from all large 167 generators 133 offered their capacity for primary frequency response cheaper than average EFR price in march 2017 (data: National Grid 2017e). Thus, the environment outside EFR looks also very competitive.

All in all, there is a relatively small number of BESS operators even after the EFR units become operational in the UK. This gives a lot of price setting power for even small players. Nevertheless, in the context of limited market size, competition flooded by BESSs and potential competitors in primary, secondary and high responses the situation signals from very unattractive competitive environment in present and in near future.

5.4.3 Hierarchy evaluation

German market is clearly preferred by volume as the national market is 65 % larger and the joint market seven times larger market by volume than in the UK. Nevertheless, German market is facing negligible growth expectations, which is the opposite in the UK. Consequently, Germany is seen only slightly superior to the UK as quantified in table 24.

From the competition point of view both markets are facing a challenging environment in terms of both indirect and direct competition. However, the UK is regarded as an underdog due to its large potential response capacity resulting from mandatory frequency response, 100 % BESS coverage in EFR and additional BESS capacity penetration through CM. Comparison matrix for competitive environment is shown in table 25.

Table 24. AHP Matrix: size and growth. Column w shows the local priorities.

	DE	UK	w
DE	1	2	0,67
UK	0,50	1	0,33

Table 25. AHP Matrix: Competitive environment. Column w shows the local priorities.

	DE	UK	w
DE	1	4	0,80
UK	0,25	1	0,20

5.5 Risks

Country specific risk profiles differ fundamentally: Germany as a more mature market is exposed more to risks related to the development of the current market, whereas the UK faces more fundamental risks related to existence of viable future market. The identified five risks are discussed and quantified below separately for both markets.

5.5.1 Risk analysis

Germany

While the market has developed together with increasing ES capacity, related risks are becoming more visible. The identified risks are decreasing prices, increasing volatility, favorable policy abandonment, increasing competition and undesirable joint tender development.

1. Decreasing PCR price level

Very limited PCR market size, its minimal growth potential, already existing PCR providers and growing ES capacity are all significant factors that increase competition in the German market. The increasing competition puts pressure on prices and carry a risk of actual price war. Furthermore, decreasing ES investment costs push ES breakeven price level down, allowing further price slide and making the position of early investors very challenging. The risk is estimated to occur with 61–90 % probability with a serious impact.

2. Increasing volatility in PCR prices

The spot volatility affects PCR volatility via conventional capacity (Hollinger et al. 2015: 5). Also the dynamics of rapidly evolving PCR capacity can have surprising effects on volatility. The increasing volatility makes price level forecasting, and consequently effective bidding, more difficult resulting in more uncertain revenues. Hence, volatility pushes PCR providers towards restrained bidding strategies with lower prices as risk of not getting accepted grows. The risk is estimated to occur with 41–60 % probability and its impact would be moderate.

3. Discharging favorable policies

Favorable tax and surcharge treatments have been in a big role in developing Germany ES sector. Unexpected negative changes would have straight impact on profits. Thus, the results would be diminishing business potential across the ES applications. With relatively stable German political movements, the occurrence probability is estimated to be unlike (11–40 %) with moderate impact.

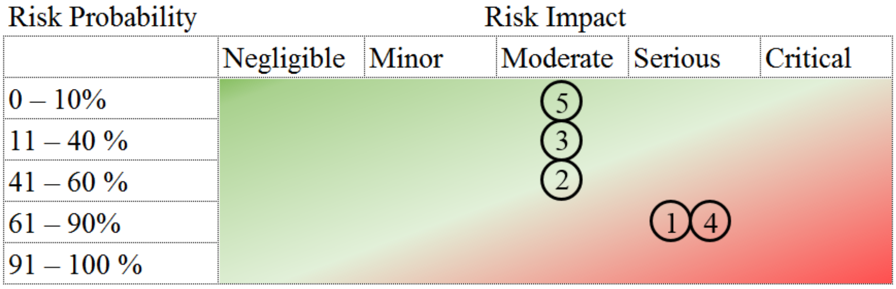
4. Increasing competition

It is clear that the competition in PCR market has increased in the recent years with increased BESS capacity. The risk of continuum is highly related to a price level risk as well, but above all it has a strong impact on bidding success. Fierce competition would inevitably push some capacity out of the market and thus endanger revenues of individual assets. The risk occurrence probability is estimated to be 61–90 % with a serious impact.

5. Unfavorable joint tender development

The joint auctions provide a unique framework with increased liquidity, larger market and currently less intense competition. Changes in import/export limitations, discharge of the joint area or further market expansion may diminish the business potential. Especially market opening for eastern European condense capacity could decrease the bidding success and impact on prices. Hence, the impact of such development would be moderate but the occurrence probability is estimated to be very small (0–10 %).

Risk positions in the risk matrix are illustrated in figure 52. Respective summarized numerical estimators (introduced in section 4.1.4) result in total riskiness indicator of 6,86 in German PCR market.



Risk Probability	Risk Impact				
	Negligible	Minor	Moderate	Serious	Critical
0 – 10%			⑤		
11 – 40 %			③		
41 – 60 %			②		
61 – 90%				①④	
91 – 100 %					

Figure 52. Risk matrix for investing in German. Numbering refers to identified risks.

The UK

The UK’s risk profile is labelled with uncertainties. The identified risks are tied strongly to major factors affecting profit generation and can be thus characterized as fundamental issues. The risks are further elaborated below and summarized in figure 53.

1. EFR Service not continued with favorable market scheme

The risk is not negligible as there is no operational experience yet and as the future market scheme is unknown. Thus, EFR might be scrapped, replaced by other response services or the whole frequency control system could be restructured resulting in uncertain revenues for BESSs. The risk is estimated to be unlike (11–40 %) with a critical impact.

2. Stagnating and over competed EFR market

For new investments EFR volume growth is essential not least because of fierce competitions with 100 % BESSs market coverage. The competition risk decreases investment potential significantly as penetrating would be very hard with proper return projections. Taking into account the growth and the capacity expectations, occurrence probability is estimated to be moderate (41–60%) with serious impact.

3. Undesirable price development

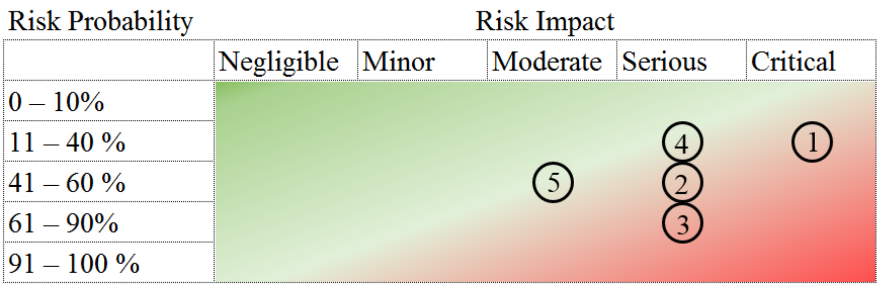
Initial EFR prices give a significant price signal for coming tenders. This combined with the competitive environment makes a significant price recovery look unlikely. In addition, the price distribution shows that even now there would be plenty of providers willing to serve under the German price level. Thus, the risk occurrence is seen likely (61–90 %) with a serious impact.

4. Unfavorable regulatory development

Regulatory ambition currently is to form a solid and a commercially viable operating framework for ESs. The development still includes a risk of unfavorable outcome especially with EU exit. For instance, the role of the distribution network operators and the payment obligation issues are currently uncertain in the UK with a potentially significant impact on ES operators. However, due to positive regulatory ambition the risk occurrence is estimated to be unlike (11–40 %) with serious impact.

5. Vanishing revenue stacking opportunities

The regulatory development might result in decreasing stacking opportunities. This is visible already as the triad revenues are advised to be removed. With potential new asset class ESs could be also marked off from the CM. As the stacking revenues are incremental and already uncertain, the occurrence (41–60 %) and impact are estimated to be moderate.



Risk Probability	Risk Impact				
	Negligible	Minor	Moderate	Serious	Critical
0 – 10%					
11 – 40 %				④	①
41 – 60 %			⑤	②	
61 – 90%				③	
91 – 100 %					

Figure 53. Risk matrix for investing in the UK. Numbering refers to identified risks.

The riskiness indicator for the UK summarizes in 7,75, which is clearly higher than in Germany. The positioning between the two is well in line with the related discussions in the earlier sections. The differences are also visible in risk matrices, where the UK has relatively high concentration in serious and critical risks.

5.5.2 Hierarchy evaluation

The difference between the riskiness indices (6,68 / 7,75) is regarded as moderate and quantified as in table 26. Due to the nature of the risks, the UK's overall risk profile exposes investors to more discrete revenues as some of the risks may completely ruin profit potential by themselves. However, it is still notable that BESS investors especially in the UK are willing to take significant risks taking into account the still low price level. The same applies to Germany with significant capacity growth and decreasing prices.

Table 26. AHP Matrix: risks. Column w shows the local priorities.

	DE	UK	w
DE	1	3	0,75
UK	0,33	1	0,25

5.6 Future development

In both markets ESs are recognized and expected to play a permanent role in future power systems. Whether the main role for BESSs is in primary frequency regulation is currently uncertain. For grid scale BESSs this is still expected to be the case at least in Germany in short to medium term future (FCBI-Energy 2015). However, additional country specific future issues that will potentially affect future market environment are discussed here.

5.6.1 Additional future aspects

Germany

Overall change of the German power system will have a significant impact also on PCR market and especially on its volatility. Hollinger et al. (2015: 5) point out that the cost of providing PCR for conventional power plants is highly dependent on the day ahead wholesale prices (opportunity cost). If increasing share of intermittent renewables influence and increase spot market price volatility, the effect on PCR market is two-sided. Firstly, volatility reflects increasing costs for conventional plants increasing their likelihood of providing PCR and thus increasing competition further (Hollinger et. al. 2015:5). This especially results from increase of idling hours in spot market. Idling is increasing with volatility as the frequency of too low prices increases respectively. On the other hand, capital costs for batteries are declining and installed capacity currently increasing. Furthermore, their cost structure will be influenced by spot volatility very little (Hollinger et. al. 2015:5). Thus, the competition in German PCR market will most probably face significant increase in future also due to these developments. Consequently, new market participants can have significant impact on current PCR providers and future prices (Hollinger et al. 2015: 1).

Notable is also that German balancing market settlement principle, pay-as-bid, has been argued and proposed to be changed to uniform pricing by several researchers (Müsgens, Ockenfels & Peek 2014: 401). Currently there is no formal actions taken to change the system. However, if proceeded, it would reduce information asymmetry exploitation possibility (Müsgens et al. 2014: 401) and reduce possibility to speculate with bidding strategies as the highest profit margin would always yield to the one with least costs. In highly competitive conditions, the uniform price could settle below BESS breakeven level and diminish the business potential. Hollinger et al (2015: 5) underline that bidding strategies play a critical role in profit generation from PCR market.

The UK

The overall power system changes in the UK will have smaller effects on EFR market than the respective changes in Germany's PCR market. This is especially due to strict EFR requirements that keep at least most conventional power plants out of the market. However, the system development affects indirectly via opportunity costs: emerging business models outside EFR may provide attractive choices potentially resulting in positive EFR price development. Such opportunities are not in sight for now, but they seem somewhat more potential in the UK with older overall energy infrastructure, more complex balancing market and more favorable attitude towards revenue stacking.

Another future aspect in the UK is more related to regulatory framework. Up to present, the distribution network operators have been active in the UK's ES sector with various R&D projects. However, whether this will continue is uncertain, as regulatory framework is not clearly defining yet if the network operators are facing ES owning and operating restrictions or not (Hassan & Dalton 2016). The same issue is under discussion in EU, but Britain's EU exit confuses the situation further. ES deployment and competition is still expected to be market based as utilities and independent developers are expected to be the primary operators in the UK's ES sector (Hassan & Dalton 2016).

5.6.2 Hierarchy evaluation

Additional future aspects do not provide significant preferences for one market over the other. However, as it is expectable that the UK's system is more robust against overall power system changes, the country is slightly preferred in AHP. This is supported also by German pay-as-bid removal speculations. The comparison is in table 27.

Table 27. AHP Matrix: additional future aspects. Column w shows the local priorities.

	DE	UK	w
DE	1	0,33	0,250
UK	3,00	1	0,750

5.7 Composed market ranking

Prevailing analysis and local priorities are composed to a global priority in table 28. Germany has an advantage in 8/10 of the criteria and thus represents relatively strong overall dominance over the UK. The UK has notable advantage only in highly speculative additional future aspects and revenue stacking opportunities. Meanwhile, Germany is not only prioritized with the rest but also represents clear distance to the UK in local priorities. As a result, global priority values are 0,77 and 0,23 for Germany and the UK respectively.

Table 28. Composed AHP results. Germany is ranked clearly better.

Criteria	1	2	3	4	5	6	7	8	9	10	W
Weight	0,22	0,26	0,04	0,08	0,11	0,04	0,03	0,15	0,05	0,03	1,00
DE	0,80	0,88	0,11	0,75	0,83	0,67	0,67	0,80	0,75	0,25	**0,77**
UK	0,20	0,13	0,89	0,25	0,17	0,33	0,33	0,20	0,25	0,75	**0,23**

Potential differences are also represented in figure 54, which illustrates potential as an area. The same conclusion is easy to make: the UK is far behind Germany. The results give clear preference for German PCR market over the UK's EFR market while indicating much higher BESS investment potential in short and medium term.

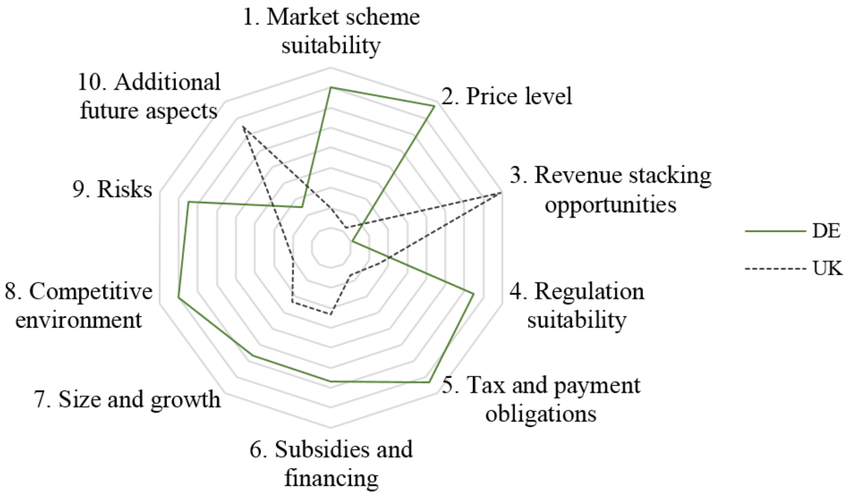


Figure 54. Global AHP priority illustration between Germany and the UK.

6 INVESTMENT SIMULATION ANALYSIS

This section illustrates results from the investment analysis with Monte Carlo Simulations. Both countries are simulated individually based on the models explained in chapter 4, but for comparison purposes the results are composed below. The results include two sections. The first one explores current profitability and its components, whilst the second part focuses on demonstrating actual profitability boundaries.

6.1 Base scenario profitability

Base scenario simulations are performed to demonstrate financial performance of hypothetical BESS investment made in near future. The starting points for MCSs are current markets with related uncertainties whilst base scenario refers to initial uncertainty parameters discussed and illustrated in section 4.3. together with model structures. However, it is to be remembered that the UK is simulated based on assumption of yearly market. Other applied assumptions are introduced in table 15. Applied total investment costs are 1,23 M€ for German 1 MW / 1,5MWh BESS and 1,01 M€ for the UK's 1 MW / 1 MWh storage as illustrated in figure 55. Results are also scalable for larger units with identical 0,67 (Germany) and 1,0 (the UK) c -rates, which are the typical values for current installations in the countries.

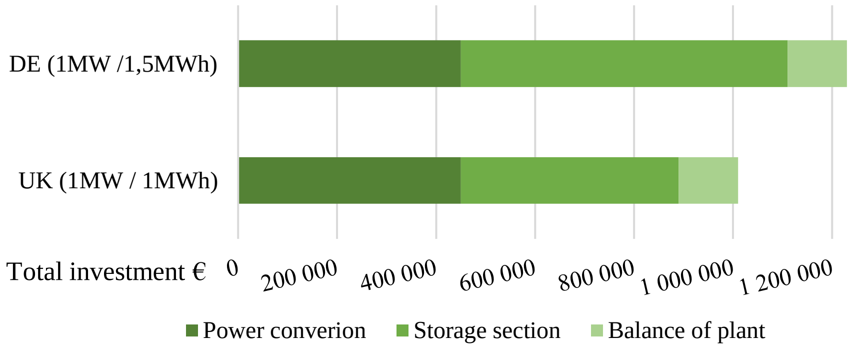


Figure 55. Applied investment cost components and total cost for BESS systems in Germany and the UK.

Base scenario simulations are run iteratively for 10 000 times. The iteration amount was validated by running 10k simulations for 10 times and comparing NPV averages and standard deviations from generated samples. The UK model was used for the purpose as it includes significantly higher variation and uncertainties. The results show only 0.02–0.51 % variation in absolute average NPV values, whilst respective standard deviation results in 0.06–1.40 % variation. Such variation is regarded very small and outputs stable taking into account the complexity of the model and amount of uncertainties involved in it. Thus, the iteration amount gives sufficient accuracy and confidence on the results.

6.1.1 Free cash flow

Free cash flow distribution represents potential for sufficient financial performance: for capital intensive industry, annual FCF should be clearly positive in order to cover initial investment cost. Positive FCF indeed is the case for both markets, but the level, fluctuation, and structure look very different. Average FCF figures and their components for whole investment horizon are illustrated in figure 56 for both countries.

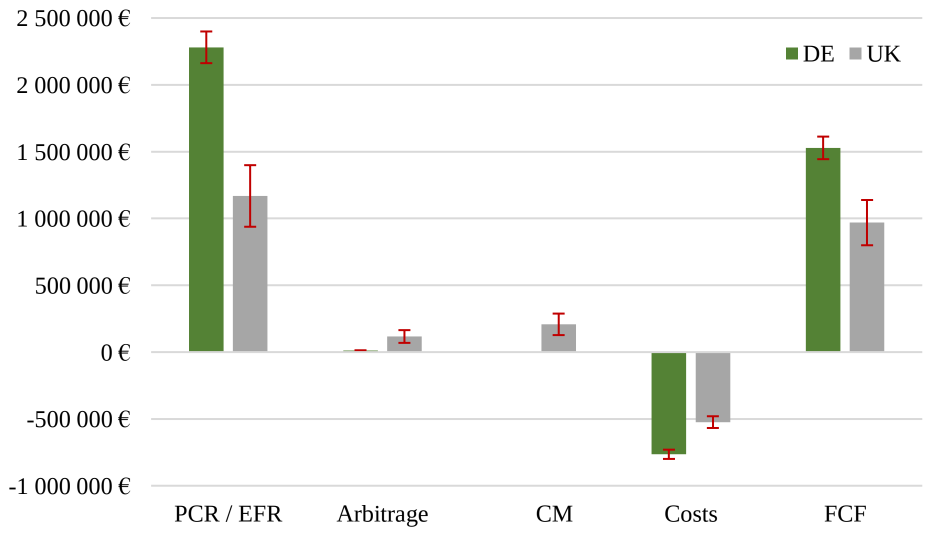


Figure 56. Average free cash flows and its components for 15 year investment horizon. Error bars represent standard deviations. Numbers are valid and scalable for BESSs with 0,67 and 1,0 c -rates in Germany and the UK respectively.

Price level analysis in section 5.2.1 indicated clearly higher revenue potential in Germany. The indication is confirmed by MCSs, which show around 1,5 M€ total average revenues during 15 years in the UK and 2,3 M€ in Germany. Variation in the UK is also a lot higher with 21 k€ standard deviation against 12 k€ in Germany. The variation reflects significantly higher uncertainty on price level variation in CM revenues in the UK. The CM revenues are slightly over 200 k€ with 80 k€ standard deviation. On the other hand, German revenues are almost solely generated from PCR -market while arbitrage and capacity market revenues count for 22 % share in total revenues in the UK. As such, average arbitrage revenues in the UK are 118 k€ while in Germany the figure is only 12 k€. There are two main factors on that. Firstly, in the UK the arbitrage is performed more due to low success rate and yearly market. Secondly, the weekly arbitrage revenues are slightly higher in the UK due to greater volatility in prices.

On cost side the aggregated average costs are around 520 k€ and 760 k€ in the UK and DE respectively. They are rather scattered among the cost components as discussed earlier in section 4.3.2–4.3.3. However, the higher costs in Germany are explained by higher corporate taxes, unavailability costs and higher required energy capacity. Nevertheless, it must be noted that excluded energy consumption related taxes are higher in the UK.

Resulting total FCF is slightly over 1,5 M€ in Germany and 0.97 M€ in the UK with 80k€ and 170 k€ standard deviations respectively. The variation is relatively strong especially in the UK. The variation is understandable when looking into annual FCFs in figure 57. Clearly visible peaks in the UK represent years in arbitrage business with and without capacity market revenues. The distribution spread reflects overall uncertainties in markets. The resulting average annual FCF in Germany is 58 % larger than in the UK with figures of 102 K€ and 64 k€ respectively. Notable is that there are no negative FCFs at all and thus operational and maintenance costs are covered every year. As such the FCF outcome reflects clearly the differences in market characteristics while indicating challenging profitability conditions.

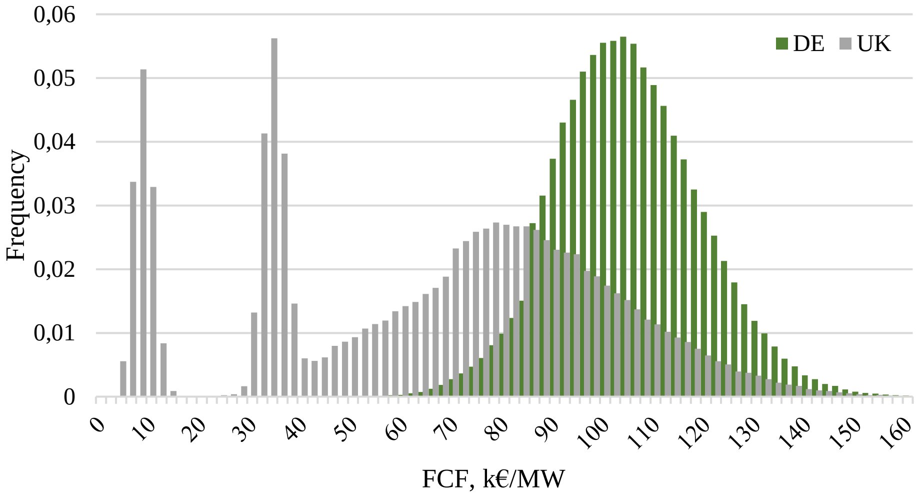


Figure 57. Simulated annual free cash flow distributions for Germany and the UK. Germany shows higher and more certain free cash flows.

6.1.2 Net present value

Valuation results confirm the hypothesis of challenging profitability. With 6 % discount rate both countries return unambiguously negative values as illustrate in figure 58. Nevertheless, not even in Germany the upper end of the valuation spread reach zero NPV. The distributions reflect again well the uncertainties as valuation spread for Germany is clearly narrower. Average NPV values are -400 k€ and -240 k€ with standard deviations of 55k€ and 112 k€ for Germany and the UK respectively. It is clear that acceptable NPV values would need significant improvements in market conditions and/or decrease in investment costs in order to financially justify investments.

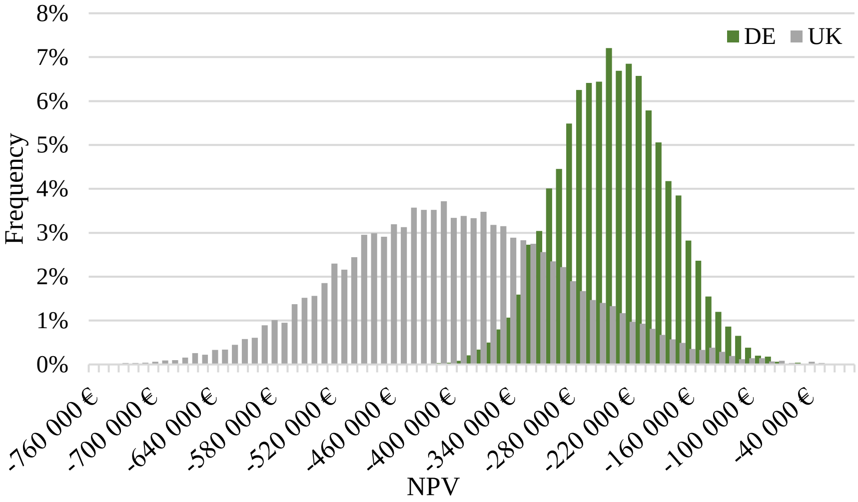


Figure 58. Net present value distributions with base scenarios assumptions and investment costs of 1,23 M€ (1 MW / 1,5 MWh) and 1,01 M€ (1 MW / 1 MWh) for Germany and the UK respectively.

The lifetime assumption in the calculations is 15 years. In contrast, payback period in Germany averages in 12,1 years and as such is relatively long: there are only few years in which the actual profit for potentially positive IRR is generated. However, FCFs discounted after 15 years are getting already relatively low and since the lifetime expectations for Li-ion BESSs are ranging from 5–15 years (Zakeri & Syri 2015: 592), the figures here are rater optimistic. Thus, increasing BESS lifetime would not change the conclusion. For the UK PBP numbers are irrelevant as most of the cases do not pay back.

6.1.3 Internal rate of return

From IRR perspective the situation looks slightly brighter at least for Germany. In the UK the situation still looks very pessimistic as only 40 % of the simulations return positive IRR. In contrast, each iteration returns positive figure for Germany. Average IRRs are 2,8 % and -0,6 % with standard deviations of 0,7 and 2,1 in Germany and the UK respectively. IRR distributions are illustrated in figure 59.

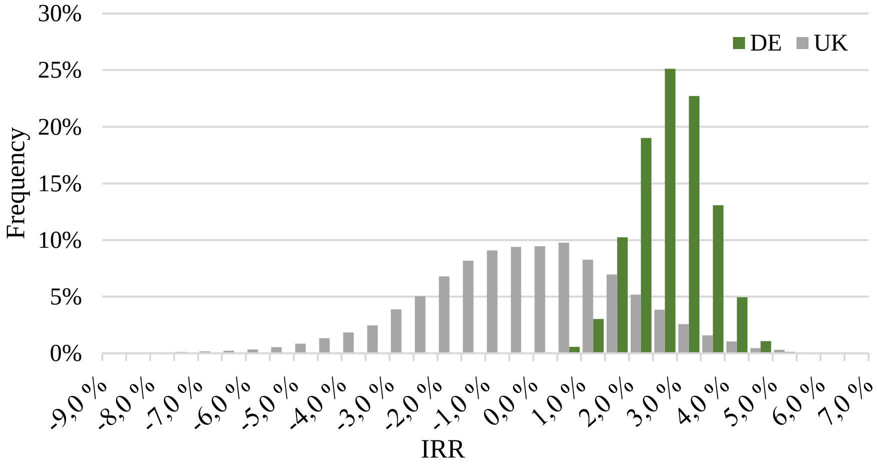


Figure 59. IRR Distributions for both markets with investment costs of 1,23 M€ (1 MW / 1,5 MWh) and 1,01 M€ (1 MW / 1 MWh) for Germany and the UK respectively.

With positive in German figures, it is to be noted that such low rates are unlike to cover even interest costs. Generally minimum return requirement is based on weighted average cost of capital (WACC), which has been 8,3 % by median for S&P 500 companies in 1994-2013 (Zenner, Junek & Chivukula 2014: 77). Zenner et al. (2014: 76) also emphasize that current low interest rates have not affected significantly WACC values as low rates have been offset by considerably stable equity cost and decreased market-based leverage. This seems to be the case also for the European energy companies which are currently under restructurings and generally have a strong leverage on balance sheet. Nevertheless, reaching WACC or reported discount rates of 9–20 % for non-cyclical industries (Zenner et al. 2014: 77) appears to be unrealistic in both countries currently.

In fact, the distributions in figure 59 reveal that there is no upside as probability to reach over 5 % IRR is negligible. The risk of losing money in the UK is obvious as 60 % of the cases would not pay back. Furthermore, the price fluctuation limits in the UK model are relatively large, thus the spread with, but still the upper tail of the distribution does not reach sufficient returns. Not even with stacked CM revenues. On the other hand, even though discounted FCFs are covering initial investment in Germany, the simulations assume very good bidding success and price level also in future, still resulting in poor IRR. As such, the returns for current investors look everything but satisfying and certain.

6.1.4 Investment decisions under current situation

Simulated business models, regarded as dominating in the chosen markets, do not provide high enough return potential so that carrying related financial risks would be straightforwardly justified. While risks and returns should be highly correlating, the business case in base scenario is biased: the risks are high but the returns very questionable. Nevertheless, decreasing electricity wholesale prices and structural industry transformation drive companies to seek for additional revenues. This drives increasing ancillary service markets competition. Thus, it is natural that BESSs as a potential asset class are getting their share of the capital allocated for new revenue explorations.

Looking at the results, the question of valuations behind already invested assets cannot be bypassed. Three main questions rise from the contradiction of the base scenario results and increasing investments in the field: are the projects justified by over optimistic hubris projections, is there strong herd behavior with a strong belief in future or is there really something to win that is not regarded in the study? The first question is easy to answer. In the light of the underlying research, if the projects are justified by financials, the assumptions behind the figures must indeed be filled with exaggerated optimism. The second one is more complicated, but when it comes to investment decisions, this issue should be narrowed down. Nevertheless, it is clear that current investors are willing to take significant risks. The last question is also multifaceted and discussed below.

Prevailing profitability figures are revealing that expected financial performance is poor for now, but still relatively close to profitability. In addition, the role of ES in future power system should not be underestimated. The strong expectation on storage need is also one of the main reasons behind the attention BESSs and ESs in general get from the power industry. Thus, most of the investing companies are probably not looking for high returns, but are willing to be involved in and learn from the development in order to gain from long term possibilities in future. Naturally, BESS for frequency regulation as a business model is getting the major attention, at least in Europe as the most potential commercial option for now. In the end, it still offers an option to penetrate the new industry with a relatively small investment (~1 M€) and gain experience and know-how for future profits.

6.2 Profitability boundary conditions

In order to illustrate how far or close the current situation is from fulfilling 6 % return target, various what-if scenarios are simulated with multiple price and investment cost combinations. Profitability boundaries are examined in terms of total investment cost (€/kW) and average PCR/EFR price by changing inputs of these parameters to the MCS models. Proportion of positive NPV outcomes out of 5000 simulations is then calculated and interpreted as a probability to reach the 6 % target. The probability is calculated from the results for each input combination and the boundary condition is regarded where 50 % of the simulations yield in positive result. In addition, the scenario analysis is performed with several bidding success rates in order to illustrate boundary condition sensitivity on biding success.

These probability figures in NPV approach are still exposed to the 6 % discount rate assumption. Hence, actual IRR values are examined with similar what-if simulations with base scenario bidding success. IRR sensitivity and values are examined in section 6.2.2.

6.2.1 Net present value target conditions

As stated before, the business potential for BESS is approaching profitability conditions in the chosen markets. However, surpassing the boundaries may seem easier than it is. Probability for positive NPV result in German market is illustrated in figure 60 and for the UK in figure 61. The shown probabilities are calculated with base scenario assumption of 95 % (Germany) and 71 % (the UK) bidding success rates. Profitability boundary conditions with different success rates are illustrated as dotted lines by positioning them around 50 % probability when calculated with the alternative rates.

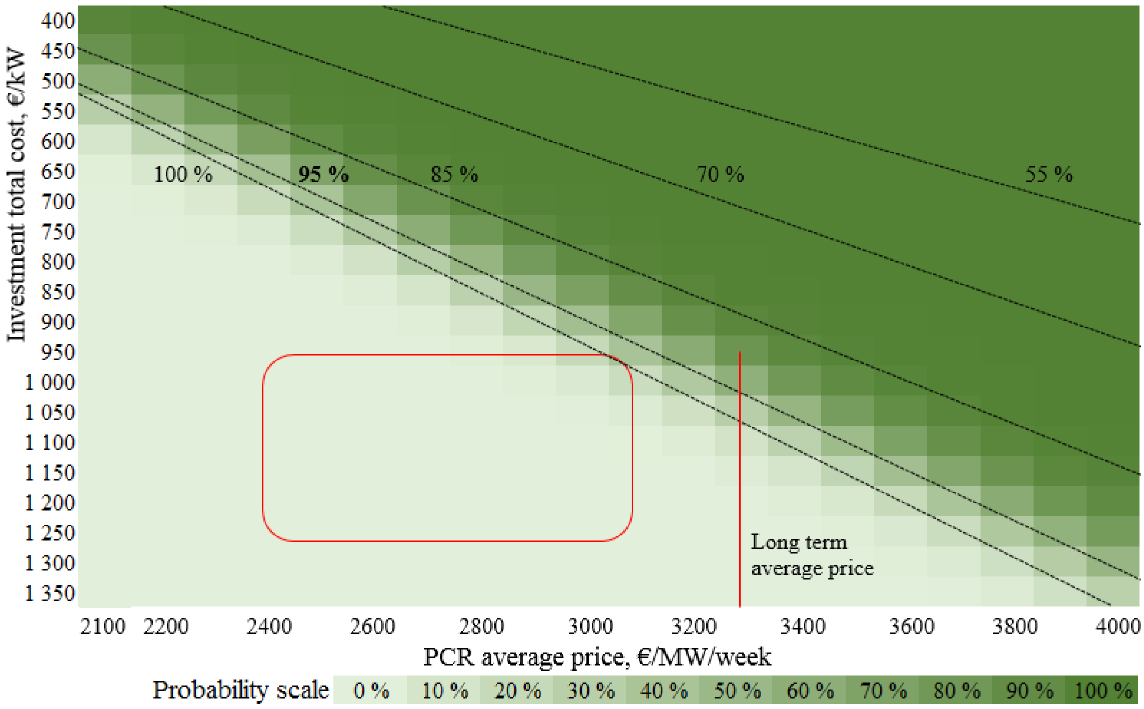


Figure 60. Probability to reach positive NPV (1 MW/1,5 MWh BESS) with 95 % bidding success in with different investment costs and PCR prices for Germany with 6 % discount rate. Profitability boundaries with different bidding success rates are marked as dotted lines and positioned in respective 50 % probability. The red box shows current situation.

The results confirm our previous view of poor changes to make profit for now. Nevertheless, it can be stated that the profitability is not that far away as the red box in figure 60 is already relatively close to profitability boundary with 95 % success rate and as the corner of the box already has some probability for a positive result. Reaching the required conditions is possible with the current investment costs, but the price level would still need to be relatively high over the next 15 years. The first four months of 2017 has realized around 2300 €/MW/week by average (data: regellaistun.net) and reaching profitability with such price would require the total cost to basically be half of the current level. Taking into account the power conversion system and balance of plant costs reaching such 650 €/kW total cost level is rather unrealistic as the storage section, i.e battery packs, itself could cost only around 50-100 €/kWh. Even in very aggressive scenarios this price level is years or even decades away from the present situation. As such, with base scenario's 95 % bidding success positive NPV result would require good above last 5 year's average price level or slight decrease in current investment cost level.

On the other hand, the boundary conditions flee quickly to unrealistically high prices and low investment costs also when the bidding success diminishes. For instance, if competition increases so that only 70 % of the BESS bids are accepted, PCR price should increase by 50 % from average of last 5 years and still investment cost should decrease at least 20 % from 2016 level. And this would yield in positive NPV with probability of 50 % and 6 % discount rate! Thus, even though the cost of BESS itself is decreasing the price expectation and confidence in bidding success must be very optimistic in order to justify investment decision with financials. In contrast, the boundaries and probabilities in the UK are illustrated in figure 61.

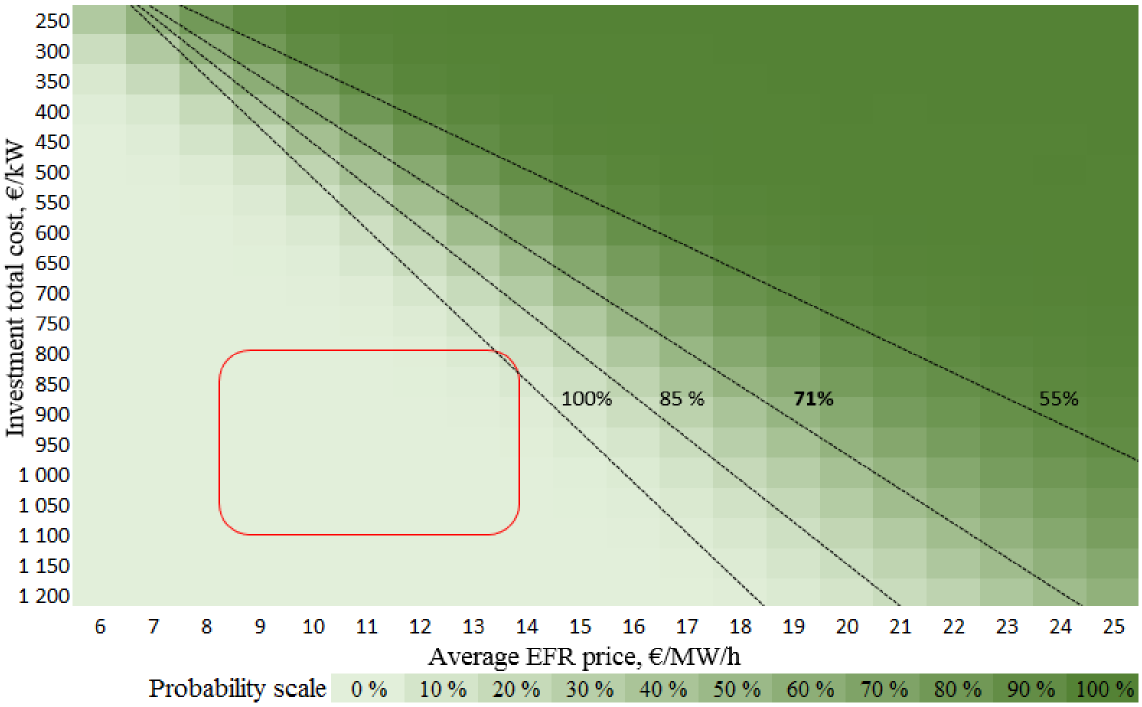


Figure 61. Probability to reach positive NPV (1 MW/1 MWh BESS) with base scenario (71 %) bidding success in relation to different investment costs and EFR price levels for the UK with 6 % discount rate. Profitability boundaries with different bidding success rates are marked as dotted lines and positioned in respective 50 % probability. The red box illustrates current situation.

For the UK the situation is much like in Germany: 100 % success rate, realistic but high price and very low current investment cost would barely meet the profitability boundary. However, with the base scenario bidding success of 71 %, the current situation is far away from favorable conditions: with applied investment cost of 1,01 M€ per 1 MW/1 MWh the EFR price level would need to double in order to surpass the profitability boundary. Notable is that such price of around 23 €/MW/h was the most frequent and weighted average price in 2016 tendering. This validates the results for one's part as well.

Sensitivity on bidding success is crucial in both markets, but it plays bigger role in Germany. This is especially due to revenue stacking opportunity in the UK. Fortunately, the future of bidding success also looks somewhat better in Germany as the market is not expected to be that saturated in near future as it is in the UK already now. Nevertheless, as increasing competition creates pressure on prices it is unlikely that the investment cost reductions would be strong enough to provide financial confidence on future profits. This applies to both markets as the profitability boundaries are getting unreachable if the market prices slide from current level and / or bidding success is diminishing.

6.2.2 Internal rate of return values

IRR values behind the prevailing NPV probabilities are illustrated in figure 62 and 63 with different investment cost and price level combinations for Germany and the UK respectively. IRR range in Germany is -5–30 % whilst in the UK it is -20–50 %. The difference is mainly due to percentually larger price spread in the UK calculations.

IRR values with different investment costs and market prices are well in line with the previous results. Within the chosen range of prices and costs 0–10 % in Germany and -10–10 % IRRs in the UK are representing clear majority of the simulated return rates. These are regarded as the most probable ranges for future investments as well as the required costs and prices remain realistic. However, above 10 % IRRs would require unrealistic prices simultaneously with significant investment cost decrease. IRR values support strongly the view that BESS investments in the chosen markets face considerable financial stress and the return rates are likely to remain relatively low in future as well.

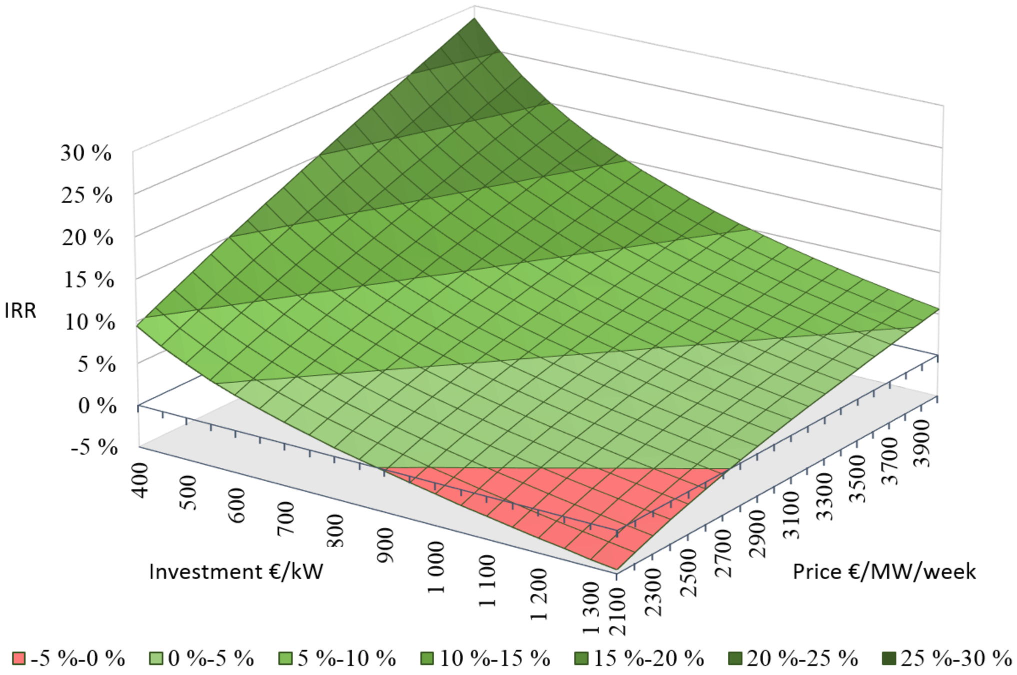


Figure 62. Internal rate of return level in relation to 1MW/1,5MWh BESS investment cost and average PCR price level in Germany. Rates are averages from 5000 simulations with 95 % bidding success.

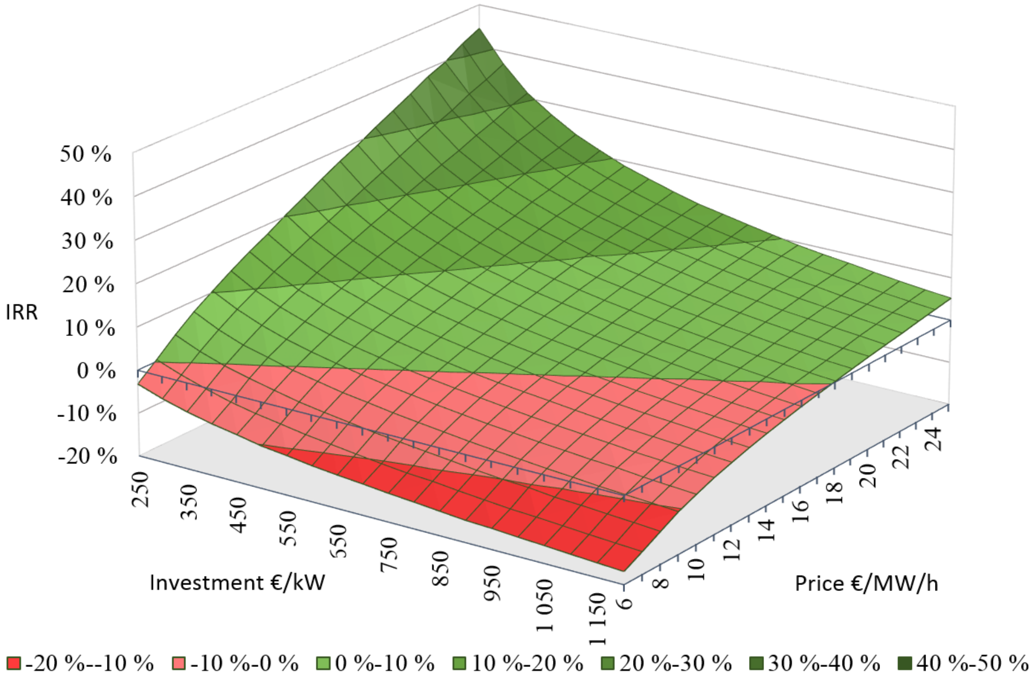


Figure 63. Internal rate of return level in relation to 1MW/1MWh BESS investment cost and average EFR price level in the UK. Rates are averages from 5000 simulations with 71 % bidding success.

6.2.3 Profitability boundary condition evaluation

Projections of Li-ion BESS cost reductions are suggesting strong decline to continue in future. The cost reductions are typically indicated for battery pack costs, which excludes power conversion and balance of plant costs. Nevertheless, the cost is forecasted to decrease as low as 100 €/kWh by 2030 (Bloomberg 2016). Similar figures for 2020–2030 are announced also by BESS manufacturer Tesla (Bloomberg 2017) and in several publications aggregated by Nykvist and Nilsson (2015: 329–332). The estimations are for battery packs for electric vehicles, but the figures are comparable for BESSs as well.

Taking into account the power conversion and plant costs, reaching 100 €/kWh costs would mean total cost of around 650 000 €/MW for 1 MW / 1 MWh BESS and 700 000 € for 1 MW / 1,5 MWh. Such investment wouldn't reach profitability boundary conditions in the UK with current average EFR price and even 100 % success rate. However, in Germany it would yield in 10 % IRR with 95 % success rate and long term average price 3300 €/MW/week. Thus, it is clear that for solid financial performance price increase is required in the UK whilst reaching sufficient profitability in Germany seems possible, but requires extremely cheap BESS, optimistic future prices and excellent bidding success.

In order to maintain constant return level, weekly price decrease of 240 €/MW in Germany would require 100 €/kW decrease in total investment cost. Consequently, if BESS becomes the dominant technology in the market and the price dynamics change to reflect new investment cost there are clear reasons for such price slide. This would yield in losses for early investors. Also Hollinger et al. (2015: 5) have brought out that BESS have the potential to change price structures in the German tenderings. Respectively, in the UK 100 €/kW decrease in total cost is equivalent to around 0.17 €/MW/h decrease in EFR price. As the competition looks fierce for the UK, the dynamics may be different anyway. This is because bids under breakeven level are more probable to succeed and thus cover even partially sunk costs involved in early invested units. As there is more capacity in construction pipeline than current EFR market size this risk is obvious. In the light of these issues, there is a clear risk that the profitability conditions will not be met before the expected pressure on prices pushes the market farther away from profitability.

7 CONCLUSIONS

The final chapter further analyses the results from chapters five and six. In addition, limitations of the study are discussed. The whole thesis is summarized in chapter 8.

7.1 Results and discussion

Initial market analysis brought up two high level points over the others. Firstly, it became clear that the frequency control markets, PCR in Germany and EFR in the UK, are well suitable for BESSs as the market schemes and earning logics form suitable commercial framework for batteries in both countries. Secondly, competitive environments, prices and more or less unclear regulation and taxation the cause main concerns for both markets. Thus, the results also confirm previous findings from Castillo and Gayme (2014: 892) that market and regulatory challenges now arise as significant barriers for commercial storage deployment. Regulatory issues have been actually well recognized, especially in Germany, while exemptions form more or less viable regulatory framework for BESSs in both markets. All in all, Germany currently dominates investment potential in 8/10 criterion and thus Germany shows clearly higher investment potential than the UK. However, neither of the markets really represent attractive investment opportunities.

Prevailing market analysis and AHP ranking results are confirmed also by market simulations, which confirmed challenging financials. Average IRR values are -0,6 % and 2,8 % for the UK and Germany respectively, whilst profitability boundary conditions reveal required very optimistic price and cost development in order to reach even 6 % IRR. In Germany it is more realistic and in fact with 2008–2016 average price and current investment costs the 6 % IRR target could be justified with 90–100 % bidding success. Simulations also show that reaching over 10 % IRR is unrealistic with the current market schemes and even remotely similar prices and costs in both countries. Thus, the market simulations conclude that BESS investment in Germany or the UK are not be justifiable by high financial returns as related risks are substantial without a respective return upside. Key findings are concluded and summarized in SCOPE -analysis in tables 29 and 30.

Table 29. Conclusion summary as SCOPE -analysis for German PCR market.

Situation	
Well-functioning capacity based pay as bid market in which BESSs cover 26 % of the capacity. Total BESS capacity growth has been 130 % (CAGR) 2013–2016 ending up in over 250 MW.	
Core competencies	**O**bstacles
1) Suitable weekly market scheme and large joint auctions with 1400 MW market size. 2) Price level still acceptable (~18€/MW/h) 3) Established regulatory treatments with favorable taxation exemptions	1) Concerning decreasing and volatile prices 2) BESS capacity still growing and tightening competition 3) Taxation and regulation still needs development
Prospects	**E**xpectations
1) National power system transformation increasing BESS potential in PCR market while providing positive outlook for other revenue sources too as conventional capacity narrows down	1) 1–5 % IRR for new investments 3) Over 10 % IRR reachable only with extremely optimistic price, cost and bidding success scenarios

Table 30. Conclusion summary as SCOPE -analysis for EFR market in the UK.

Situation	
Primary EFR market opened in 2016 with 200 MW new capacity, which will start operating in 2017/18. BESS cover the whole market with initial four year contracts through capacity based pay-as-bid tendering. Overall investment potential less attractive than in Germany.	
Core competencies	**O**bstacles
1) EFR market excepted to moderately grow 2) Technical requirements BESS favorable 3) Favorable service availability requirements 4) Capacity market revenue stacking	1) No certain information of future market scheme or even existence 2) EFR price level very poor (~11 €/MW/h) 3) Unclear regulatory situation with potential double charging 4) Large BESS capacity (>500 MW) penetration through capacity market at latest 2020/21 increasing straight competition.
Prospects	**E**xpectations
1) Potential short term EFR market offers new potential if established 2) Anticipated regulatory development supports commercial potential	1) -3–3 % IRR realistic 3) Over 10 % IRR unreachable without fundamental price increase

There still is a recognized and anticipated ESs need in presetn and in future in both countries while BESS cost and technology development has taken great steps towards maturity. Still as seen business opportunities for new investments have been limited. As the installed capacity is growing, these limited opportunities incur strong investment willingness. This willingness is supported by challenging overall power market development pushing companies towards new revenue streams. However, looking at the research results, it can be asked if the best investment time already passed by. In Germany the prices were clearly higher in the past years with good bidding success whilst initial contracts for 15 years in capacity market and for four years in EFR market secured over 0,8 M€/MW cash flows for some of the UK participants. Thus, the actual profitability figures for some existing assets might look better than the ones for future investments. If the development is continuing purely market based, questionable is, whether seen prices in Germany or long fixed contracts in the UK provide such opportunities in future.

On the other hand, it is to be noted that the study covers just one business model. In Germany PCR is indeed seen as a main market for grid scale BESS currently and in short to medium term future (FCBI-Energy 2015). Nevertheless the business models are evolving constantly and as flexible BESSs are capable to provide several services it might be that within the 15 year investment horizon existing units will generate profits from completely different revenue sources than anticipated. In the UK, the business models are evolving even more. Although, EFR provides by far the best market for BESSs, it is not still the only option. Indeed, Lian et al. (2017) already showed in the UK case that BESSs could provide 100 % of primary, secondary and high response need cheaper than market prices in an optimal case. This of course does not prove commercial viability for individual investors, but confirms that there are other potential markets applicable as well.

Nevertheless, as reaching sufficient over 10 % IRR levels with BESS in Germany or the UK seems a bit unrealistic in current light, the whole ES sector appears indeed quite unattractive. In fact, there is a dilemma as strong investment willingness and also system need for ESs increase investment pressure but increasing installations make the market less attractive by pushing price down in service side and cannibalizing arbitrage value on the other side. In addition, decreasing BESS costs give incentive to wait further.

Within the framework of increasing BESS capacity and very narrow profit potential one additional conclusion can be drawn: at the moment there is something to win and earn with BESS investments in Germany and the UK but it is not profit. The BESS investments for the markets are not justified primarily by financial rewards. Instead, they provide an opportunity to join emerging industry sector with a relatively small investment as a strategic step towards anticipated larger future energy storage business. This is the case and enough to attract investments even though the future business models are unknown.

7.2 Future research

The study has applied novel Monte Carlo simulations valuation framework for ES investments. Thus it provides suggestion for Zafirakis et al. (2013: 138) who point out that "absence of an integrated valuation framework for services provided by energy storage technologies, owed to its limited scope so far, hinders investments in such capital intensive systems". However, further research demand remains when applying and simulating uncertainties with investment analysis. Especially actual market success effects could be researched more in depth. This should be expanded to cover also wholesale energy markets: how much reached revenues differ from optimal asset utilization and what would have been the effect on investment valuations if known before.

Another interesting research topic arises from demand side management. In the UK there is a separate market for the service whilst in Germany demand response is included in PCR market. Thus, in the UK it would be relevant to study market and price behaviors between demand response and other frequency response services. In fact, demand response and BESSs are providing similar flexibility in power system and it is reasonable to ask whether batteries can compete with large scale demand response in cost sense.

7.3 Reliability and limitations

Market analysis and especially AHP results in section five are exposed to objective considerations. However, evaluated information is inaugurated for the reader in order to increase transparency. In addition, in most cases the differences between Germany and the UK are clearly preferring one over the other keeping the relative distance in local priorities somewhat long. Ending up in opposite ranking would need a completely different interpretation of objective market information, which is not relevant in this study. Hence, the ranking results and conclusions are seen reliable and unbiased as such.

It has been also pointed out earlier that the results from MCSs are scalable for units with identical c-rates in both countries. Nevertheless, also MCS results are somewhat subjective. The models indeed include relatively much subjective estimations and assumptions especially regarding bidding success rates and prices. These are significant result contributing parameters and thus affect the conclusions. On the other hand, this is one of the main reasons why MCS was chosen for the study: it allows simulating basically whole range of different price scenarios and bidding successes. Thus, the results are not exposed to subjective individual scenarios, but show the whole distribution of probable outcomes within chosen scenario range. Furthermore, the input parameter ranges (e.g. prices) are justified with realizations and expanded with ample margins and thus regarded covering the whole range of relevant values. As the univocal MCS results do not leave too much room for doubts concerning the financial attractiveness and as the simulations are also carried out with different bidding success rates, the results and conclusions here are also regarded relevant and reliable.

Nevertheless, naturally the price distributions, estimated parameters, regulation and whole market environments will develop greatly during the next 15 years. This is especially the case in power industry with significant ongoing changes. Thus, it must be emphasized that the study deals with a relatively new field involving a large degree of freedom.

8 SUMMARY

The thesis focuses on exploring, comparing and simulating battery energy storage investment potential in primary frequency control market in Germany and in enhanced frequency response market in the UK. The study first discusses frequency control principles and markets, which is then followed by brief energy storage technology discussion and introduction to potential revenue streams. After the prevailing theory and background chapters, methodology sections introduce the used research methods: online market research, Analytical Hierarchy Process (AHP) and Monte Carlo simulations.

The study set three research questions. The first question concerns market attractiveness, which is evaluated with online market research including ten different aspects. The results reveal silent market attractiveness with suitable market schemes and solid cash flow generation principle but with limited market size and growth potential, risky competitive outlook and concerning prices. These issues hold for both markets but, as an answer to the second question of the preferred market, AHP results suggest that Germany has clearly higher potential than the UK. Finally, Monte Carlo simulation results with investment analysis are shown in order to answer the third question of financial performances for hypothetical investments. The simulation results reveal poor average internal rate of returns around 2,8 % and -0,6 % for Germany and the UK respectively. The return distributions show low profitability (<6%) even with optimistic market price development. Whereas, profitability boundary conditions show that 6 % return rate is reachable in Germany but the UK requires price increase. It was also shown that over 10 % returns would require overoptimistic market and cost development in both countries.

Finally, the study concludes that battery energy storage investments are not justified primarily by expected returns but they provide an opportunity to join emerging industry sector with a relatively small investment. This can be considered as a strategic step towards anticipated future energy storage business by starting learning and development process now. The study also confirmed that frequency control markets in Germany and the UK provide more commercial potential than earlier studied arbitrage related revenues.

REFERENCES

Literature references:

Aditya, S.K. & D. Das (2001). Battery energy storage for load frequency control of an interconnected power system. *Electric Power Systems Research*, 58: 3, 179–185.

Aghamohammadi, M.R. & H. Abdolahinia (2014). A new approach for optimal sizing of battery energy storage system for primary frequency control of islanded Microgrid. *International Journal of Electrical Power & Energy Systems*, 54, 325–333.

Ahram, A. (2011). Concepts and Measurement in Multimethod Research. *Political Research Quarterly,* 66:2, 280–291.

Al-Harbi, K.M.A. (2001). Application of the AHP in project management. *International Journal of Project Management*, 19: 1, 19–27.

Allan. I, Wilson, G., McGregor, P. & P. Hall (2010). Energy storage in the UK electrical network: Estimation of the scale and review of technology options. *Energy Policy*, 38: 8, 4099–4106.

Belhomme, R., Trotignon, M., Cantenot, J., Dallagi, A., Cerqueira, E., Hoffmann, B., Burger, J. & J. Eberbach (2016). Overview of the electricity system market and service layers in France, UK and Germany. *International Conference on the European Energy Market, EEM*, Porto, Portugal, 1–5.

Bradbury, K., Pratson L. & D. Patiño-Echeverri (2014). Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. *Applied Energy* 114, 512–519.

Brandimarte, P. (2014). *Handbook in Monte Carlo Simulation*. Hoboken: Wiley

Castillo, A. & D.F. Gayme (2014). Grid-scale energy storage applications in renewable energy integration: A survey. *Energy Conversion and Management.* 87, 885–894.

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

Cho, J., Jeong, S. & Y. Kim (2015). Commercial and research battery technologies for electrical energy storage applications. *Progress in Energy and Combustion Science*, 48, 84–101.

Connolly, D., Lund, H., Finn, P., Mathiesen, B.V. & M. Leahy (2011). Practical operation strategies for pumped hydroelectric energy storage (PHES) utilising electricity price arbitrage. *Energy Policy*, 39: 7, 4189–4196.

Divya, K.C. & J. Østergaard (2009). Battery energy storage technology for power systems–An overview. *Electric Power Systems Research,* 79: 4, 511–520.

Erol, Ö. & B. Kılkış (2012). An energy source policy assessment using analytical hierarchy process. *Energy Conversion and Management*, 63, 245–252.

Feilzer, Y. (2010). Doing Mixed Methods Research Pragmatically: Implications for the Rediscovery of Pragmatism as a Research Paradigm. *Journal of Mixed Methods Research*, 4:1, 6–16.

Ferreira, H.L., Garde, R., Fulli, G., Kling, W. & J.P. Lopes (2013). Characterisation of electrical energy storage technologies. *Energy*, 53, 288–298.

Fouad J. & A. Jabir (2015). Risk matrix model applied to the outsourcing of logistics' activities. *Journal of Industrial Engineering and Management* 8:4, 1179–1194.

Franek, J. & A. Kresta (2014). Judgment Scales and Consistency Measure in AHP. *Procedia Economics and Finance*, 12, 164–173.

Gallo, A., Simões-Moreira, J., Costa, H, Santos, M & E. Moutinho dos Santos (2016). Energy storage in the energy transition context: A technology review. *Renewable and Sustainable Energy Reviews*, 65, 800–822.

Hesse-Biber, S. & A. Griffin (2012). Internet-Mediated Technologies and Mixed Methods Research: Problems and Prospects. *Journal of Mixed Methods Research*, 7:1, 43–61.

Hesse-Biber, S. (2010). *Mixed Methods Research: Merging Theory with Practice*. New York : Guilford Press.

Hollinger, R., Diazgranados, L.M. & T. Erge (2015). Trends in the German PCR market: Perspective for battery systems. 2015 12th International Conference on the European Energy Market (EEM), 1–5.

Kroese, D. P., Brereton, T., Taimre, T. & Z. I. Botev (2014). Why the Monte Carlo method is so important today. WIRES Computational Statistics, 6:6, 386–392.

Lian, B., Sims, A. Yu, D., Wang, C & R. Dunn (2017). Optimizing LiFePO4 Battery Energy Storage Systems for Frequency Response in the UK System. *IEEE Transactions on Sustainable Energy*, 8:1, 385–394.

Lieberman, E. (2005). Nested Analysis as a Mixed-Method Strategy for Comparative Research. *American political science review*, 99:3, 435–452.

Luo, X., Wang, J., Dooner, M. & J. Clarke (2015). Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Applied Energy*, 137, 511–536.

Mahlia, T., Saktisahdan, T., Jannifar, A., Hasan, M. & H. Matseelar (2014). A review of available methods and development on energy storage; technology update. *Renewable and Sustainable Energy Reviews*, 33, 532–545.

Müsgens, F., Ockenfels, Axel. & M., Peek (2014). Economics and design of balancing power markets in Germany. *Electrical Power and Energy Systems* 55, 392–401.

Nykvist. B. & M. Nilsson (2015). Rapidly falling costs of battery packs for electric vehicles. Nature Climate Change, 5:4, 329–332.

Pan, X., Xu, H., Song, J. & C. Lu (2015). Capacity optimization of battery energy storage systems for frequency regulation. 2015 *IEEE International Conference on Automation Science and Engineering (CASE)*, Gothenburg, Sweden, 1139–1144.

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

Pearre, N. & L. Swan (2015). Technoeconomic feasibility of grid storage: Mapping electrical services and energy storage technologies *Applied Energy* 137, 501–510.

Pirbazari, A. M. (2010). Ancillary services definitions, markets and practices in the world. Sao Paulo: 2010 IEEE/PES Transmission and Distribution Conference and Exposition: Latin America (T&D-LA), 32–36.

Saaty, T. (1980). *The Analytic Hierarchy Process, Planning, Piority Setting, Resource Allocation*. New York: McGraw-Hill.

Saaty, T. (1990). How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research*, 48: 1, 9–26.

Sanders, N. & S. Wagner (2011). Multidisciplinary and Multimethod Research for Addressing Contemporary Supply Chain Challenges. *Journal of Business Logistics*, 32: 4, 317–323.

Saulny, N. (2017). Operation and Profitability of Batteries in Electricity Reserve Markets. Aalto University. Department of Energy Technology. Master’s thesis.

Sioshansi, R. (2010). Welfare Impacts of Electricity Storage and the Implications of Ownership Structure. *Energy Journal* 31: 2, 173–198.

Staffell, I. & M. Rustomji (2016). Maximising the value of electricity storage. *Journal of Energy Storage* 8, 212–225.

Steffen B. (2012). Prospects for pumped-hydro storage in Germany. *Energy Policy* 45, 420–429.

Subramanian, N. & R. Ramanathan (2012). A review of applications of Analytic Hierarchy Process in operations management. *International Journal of Production Economics*, 138: 2, 215–241.

Swierczynski, M. Stroe, D.I., Stan, A.I. & R. Teodorescu (2013). Primary frequency regulation with Li-ion battery energy storage system: A case study for Denmark. *ECCE Asia Downunder (ECCE Asia), 2013 IEEE*, 487–492.

Xu, B. (2014). BESS Control Strategies for Participating in Grid Frequency Regulation. *IFAC Proceedings Volumes*, 47: 3, 4024–4029.

Zafirakis, D., Chalvatzis, K.J., Baiocchi, G. & G. Daskalakis (2016). The value of arbitrage for energy storage: Evidence from European electricity markets. *Applied Energy*, 184, 971–986.

Zakeri, B. & S. Syri (2015). Electrical energy storage systems: A comparative life cycle cost analysis. *Renewable and Sustainable Energy Reviews,* 42, 569–596.

Zenner, M., Junek, E. & R. Chivukula (2014). Bridging the Gap between Interest Rates and Investments. *Journal of Applied Corporate Finance,* 26: 4, 75–80.

Zhang, Y. J. (2016). Profit Maximizing Planning and Control of Battery Energy Storage Systems for Primary Frequency Control. *IEEE Transactions on Smart Grid*, 99, 1–13.

Zhao, H., Wu, Q., Hu, S., Xu, H. & C. Rasmussen (2015). Review of energy storage system for wind power integration support. *Applied Energy*, 137, 545–553.

Online references:

Bloomberg (2016). Batteries Storing Power Seen as Big as Rooftop Solar in 12 Years [online]. [27.4.2017]. Available: www.bloomberg.com/news/articles/2016-06-13 /batteries-storing-power-seen-as-big-as-rooftop-solar-in-12-years

Bloomberg (2017). Tesla’s $169 Million Battery Play Is Just the Beginning [online]. [2.5.2017]. Available: https://www.bloomberg.com/news/articles/2017-03-17 /tesla-s-169-million-battery-play-is-just-the-beginning.

Bundesnetzagentur (2017). Energy storage regulation in Germany. Email to Samuli Kivipelto 31.3.2017

Bundesverband der Energie- und Wasserwirtschaft (2017). BDEW-Strompreisanalyse Februar 2017 [online]. [4.4.2017]. Available: https://www.bdew.de/internet.nsf/id /bdew-strompreisanalyse-de

Consentec (2012). Market Study on a Common Market for Primary Control Reserve in the Netherlands and Germany [online]. [1.3.2017], 1–25. Available: www.acm.nl/download /documenten/nma/103542%20Consentec%20rapport.pdf

Department for Business, Energy & Industrial Strategy (UK) (2016). Electricity Market Reform: Capacity Market [online]. [17.3.2017]. Available: www.gov.uk/government/collections/electricity-market-reform-capacity-market

Department for Energy & Climate Change (DECC) (2016). Cutting Red Tape - Review of the energy sector [online]. [17.3.2016], 1–24. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file /504797 /bis-16-158-crt-review-energy.pdf

Eex.com (2017). Market Data [online]. [12.5.2017]. Available: www.eex.com/en/market-data/power/spot-market

Energy and Climate Change Committee (UK Parliament) (2016). The energy revolution: preparing for the future UK energy system [online]. [23.3.2017]. Available: https://www.publications.parliament.uk/pa/cm201617/cmselect/cmenergy/705/70505.htm

ENTSO-E (2009). Continental Europe Operation Handbook: P1 Load-Frequency Control and Performance, Final Version [online]. [24.2.2017]. Available: https://www.entsoe.eu/publications/system-operations-reports /operation-handbook/Pages/default.aspx

ENTSO-E (2013). Network Code on Load-Frequency Control and Reserves [online]. [27.2.2017]. Available: https://www.entsoe.eu/major-projects /network-code-development/load-frequency-control-reserves/Pages/default.aspx

ENTSO-E (2015c). Regional Group Great Britain [online]. [13.3.2017]. Available: https://www.entsoe.eu/about-entso-e/system-operations/regional-groups /great-britain /Pages/default.aspx

ENTSO-E (2017a). Balancing and Ancillary Services Markets [online]. [24.2.2017]. Available: https://www.entsoe.eu/about-entso-e/market/ balancing-and-ancillary-services-markets/Pages/default.aspx

ENTSO-E (2017b). Continental Europe Operation Handbook: Appendix 1, Load-Frequency Control and Performance [online]. [24.2.2017]. Available: www.entsoe.eu/publications/system-operations-reports/operation-handbook /Pages/default.aspx

European Commission (2013). Commission Regulation (EU) No 543/2013 on submission and publication of data in electricity markets and amending Annex I to Regulation (EC) No 714/2009 of the European Parliament and of the Council.

Eurostat (2015). Electricity Prices – Price Systems [online]. [6.3.2017], 1–253. Available: ec.europa.eu/eurostat/documents/38154/42201/Electricity-prices-Price-systems-2014.pdf /7291df5a-dff1-40fb-bd49-544117dd1c10

Eurostat (2016). Electricity price statistics [online]. [6.3.2017]. Available: ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics

FCBI-Energy (2015). Energy Storage Update: Germany’s power market reforms provide platform for storage growth [online]. [1.3.2017]. Available: http://analysis.energystorageupdate.com /germanys-power-market-reforms-provide-platform-storage-growth

Federal Ministry for Economic Affairs and Energy (Germany) (2017a). Funding programmes for energy storage [online]. [6.3.2017]. Available: www.bmwi.de/Redaktion/EN/Artikel/Energy/foerderinitiative-energiespeicher.html

Federal Ministry for Economic Affairs and Energy (Germany) (2017c). Electricity Market of the Future [online]. [28.3.2017]. Available: http://www.bmwi.de/Redaktion/EN/Dossier /electricity-market-of-the-future.html

Fitzgerald. G., Mandel, J., Morris. J. & H. Touati (2015). The Economics of Battery Energy Storage [online]. [3.5.2017], 1–41. Boulder: Rocky Mountain Institute. Available: rmi.org/insights/search-sector-program /economics-battery-energy-storage/

Germany Trade & Invest (GTAI) (2016). The Energy Storage Market in Germany [online]. [1.3.2017]. Available: https://www.gtai.de/GTAI/Content/EN/Invest /_SharedDocs/Downloads/GTAI/Fact-sheets/Energy-environmental /fact-sheet-energy-storage-market-germany-en.pdf?v=7

Hassan, M. & L. Dalton (2016). CMS Guide to Energy Storage: United Kingdom [online]. [17.3.2017]. Available: https://eguides.cmslegal.com/energy_storage

International Energy Agency (IEA) (2014). Technology Roadmap – Energy storage [online]. [10.5.2017], 1–64. Available: www.iea.org/publications/freepublications /publication/TechnologyRoadmapEnergystorage.pdf

Janzen. D. & A. Wippich (2016). CMS Guide to Energy Storage: Germany [online]. [4.4.2017]. Available: https://eguides.cmslegal.com/energy_storage

Just, S. (2015). *The German Market for System Reserve Capacity and Balancing Energy* [online]. Essen: University of Duisburg-Essen. [1.3.2017], 1–38. Available: www.ewl.wiwi.uni-due.de/fileadmin/fileupload/BWL-ENERGIE/Arbeitspapiere/RePEc /pdf/wp1506_Just2015TheGermanMarketForSystemReserveCapacityAndBalancing.pdf

National Grid (2016a). Future Requirements for Balancing Services [online]. [13.3.2017], 1–29. Available: www2.nationalgrid.com/WorkArea /DownloadAsset.aspx?id=8589935072

National Grid (2016b). Final TNUoS tariffs for 2016/17 [online]. [17.3.2017], 1–31. Available: www2.nationalgrid.com/UK/Industry-information/System-charges /Electricity-transmission/Approval-conditions/Condition-5/

National Grid (2016c). Provisional Auction Results [online]. [17.3.2017]. Available: https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library /Provisional%20Results%20Report%20-%20T-4%202016.pdf

National Grid (2016d). EFR tender round 1 tender results [online]. [20.3.2017]. Available: http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx

National Grid (2016f). Enhanced Frequency Response - Frequently Asked Questions [online]. [20.3.2017], 1–29. Available: http://www2.nationalgrid.com /Enhanced-Frequency-Response.aspx

National Grid (2017a). Application of European Network Codes to GB [online]. [13.3.2017]. Available: http://www2.nationalgrid.com/UK/Industry-information /Electricity-codes/European-network-code/application-of-network-codes-to-gb/

National Grid (2017b). Firm Frequency Response (FFR) [online]. [13.3.2017]. Available: http://www2.nationalgrid.com/UK/Services/Balancing-services/Frequency-response /Firm-Frequency-Response/

National Grid (2017d). Enhanced Frequency Response [online]. [20.3.2017]. Available: http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx

National Grid (2017e). Outcome - Energy Services [online]. [22.3.2017]. Available: www2.nationalgrid.com/UK/Industry-information /Electricity-transmission-operational-data /Data-explorer/Outcome-Energy-Services/

National Grid (2017f). Mandatory Frequency Response [online]. [5.5.2017]. Available: http://www2.nationalgrid.com/uk/services/balancing-services/frequency-response /mandatory-frequency-response/

Nord Pool AS (2017). Historical Market Data [online]. [20.4.2017]. Available: http://www.nordpoolspot.com/historical-market-data/

Norton Rose Fulbright (2017). Energy storage in Germany - what you need to know [online]. [30.3.2017]. Available: www.nortonrosefulbright.com/knowledge /publications/147129/energy-storage-in-germany-what-you-need-to-know

Ofgem (2017a). The GB electricity transmission network [online]. [17.3.2017]. Available: https://www.ofgem.gov.uk/electricity/transmission-networks /gb-electricity-transmission-network

Ofgem (2017b). Low Carbon Network Fund [online]. [22.3.2017]. Available: https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation /low-carbon-networks-fund

Ofgem (2017c). Buy-out prices and obligation levels 2010-11 – 2017-18 [online]. [23.3.2017]. Available: https://www.ofgem.gov.uk/publications-and-updates /renewables-obligation-ro-buy-out-price-and-mutualisation-ceilings-2017-18

Ofgem (2017d). Feed-in Tariff Annual Levelisation Notice 2015–2016 [online]. [23.3.2017]. Available: https://www.ofgem.gov.uk/publications-and-updates/ feed-tariff-annual-levelisation-notice-2015–2016

Papapetrou, M., Maidonis, T., Garde, T. & G. Garcia (2013). European Regulatory and Market Framework for Electricity Storage Infrastructure [online]. Münich: WIP & Navarra: CENER. [29.3.2017], 1–44. Available: www.store-project.eu /documents/results/en_GB/european-regulatory-and-market-framework-for-electricity-storage-infrastructure.

Regelleisgtung.net (2017b). International PCR cooperation: coupling of German, Belgian, Dutch, French, Swiss and Austrian markets [online]. [28.2.2017]. Available: https://www.regelleistung.net/ext/static/prl

Regelleistung.net (2017a). Market for control reserve in Germany [online]. [28.2.2017]. Available: https://www.regelleistung.net/ext/static/market-information?lang=en

Regelleistung.net (2017c). Prequalification procedure for the provision and activation of control reserve [online]. [28.2.2017]. Available: https://www.regelleistung.net/ext/static/prequalification?lang=en

Regelleistung.net (2017d). Common tendering for primary control reserve [online]. [28.2.2017]. Available: https://www.regelleistung.net/ext/static/prl

Regelleistung.net (2017e). Prequalified providers [online]. [30.3.2017]. Available: https://www.regelleistung.net/ext/

Regelleistung.net (2017f). Data centre [online]. [12.5.2017]. Available: https://www.regelleistung.net/ext/tender/

Research Council UK (RCUK) (2017). Storage [online]. [22.3.2017]. Available: http://www.rcuk.ac.uk/research/xrcprogrammes/energy/EnergyResearch/storage/

Sandia National Laboratories (2017). DOE Global Energy Storage Database [online]. [1.3.2017]. Available: https://www.energystorageexchange.org/projects

Schoenung. S. (2011). Energy storage systems cost update [online]. New Mexico: Sandia National Laboratories [24.4.2017]. Available: https://digital.library.unt.edu/

The Office of Gas and Electricity Markets (Ofgem) (2016). Open letter: Charging arrangements for embedded generation [online]. [17.3.2017]. Available: https://www.ofgem.gov.uk/system/files/docs/2016/07 /open_letter_-_charging_arrangments_for_embedded_generation.pdf

Government of the UK (2016). Climate Change Levy rates [online]. [23.3.2017]. Available: https://www.gov.uk/government/publications/rates-and-allowances-climate-change-levy /climate-change-levy-rates

Government of the UK (2017a). Electricity Market Reform: Contracts for Difference [online]. [23.3.2017]. Available: https://www.gov.uk/government/collections /electricity-market-reform-contracts-for-difference

Government of the UK (2017b). Notice CCL1/3: Climate Change Levy - reliefs and special treatments for taxable commodities [online]. [16.5.2017]. Available: www.gov.uk /government/publications/excise-notice-ccl13-climate-change-levy-reliefs-and-special-treatments-for-taxable-commodities

Zeh, A., Müller, M., Naumann, M., Hesse, H.C., Jossen, A. & R. Witzmann (2016). Fundamentals of Using Battery Energy Storage Systems to Provide Primary Control Reserves in Germany [online]. *Batteries* 2: 3 [22.5.2017], 1–21. Available: http://www.mdpi.com /2313-0105/2/3/29

Legislation references:

The Electricity Order 2001 No. 3270 (UK Statutory Instruments), 28.9.2001.

Energiewirtschaftsgesetz (EnWG, German law), 1.12.2012.

Erneuerbare-Energien-Gesetz (EEG, German law), 8.7.2016.

Stromsteuergesetz (StromStG, German law), 23.12.2016.

Appendix 1: Case Poland

The study was initially planned to cover also Polish primary frequency control market. However, due to unestablished Polish market and escalating scope of the study the country was dropped out. Initial analysis for the country is summarized here.

Technically and by principle primary control in Poland is identical to Germany due to shared synchronized frequency control area, in which Poland contributes with around 170 MW of primary control. The balancing market and related operations are centrally operated by Polish TSO (PSE). Nevertheless, Poland utilizes centrally dispatched generation system in which all units with over 100 MW capacity are obliged to offer their balancing capacity for TSO in all balancing levels. Thus, there are currently no frequency control markets suitable for battery energy storages. In addition, reimbursement for the primary control service is fixed to 5 % of the variable costs of the potential energy generation with the capacity reserved for the service. Delivered energy is paid too, but it shows minor role. Thus, the payment logic is not sufficient for batteries for now.

On the other hand, Polish TSO and ministry of energy are seen supportive towards energy storage development. Polish new renewable energy law (2016) also recognizes and defines energy storages. Other ES specific legislation concerning batteries is not established. In addition, Polish power markets have been pushed for more competitive set-up from national and from EU. This pressure includes also balancing and frequency control markets. This together with aging power infrastructure and TSOs and ministry’s compliance towards system and market development gives good reasons to anticipate favorable market development in future from battery energy storage point of view.

Undeveloped storage sector in Poland has very limited references. There is currently 1,7 GW of pumped hydro capacity but only one installed battery system with 0,75 MW/1,5 MWh capacity. It is operating in local renewables shifting. As a conclusion, interest towards batteries has increased also in Poland together with positive market expectations for a long term. Unfortunately, there is no commercial market potential for now.