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MSc in Energy: Strategy, Law & Economics

THESIS TITLE:

PARTICIPATION OF BATTERY ENERGY STORAGE SYSTEM IN THE GERMAN ENERGY MARKET

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Abstract

The increasing generation capacity of renewable energy sources poses new challenges to the electrical power systems due to their volatile and intermittent injection. The progress in battery energy storage systems aims to guarantee the stability of the energy power systems by contributing to the provision ancillary services.

In this thesis, we examine the participation of battery energy storage systems in the German Primary Control Response market. At first, the importance of the integration of Battery Energy Storage Systems in the power grids is highlighted, whereas in the next chapter the available balancing services in the European energy markets are presented. In Chapter 4, the German power system and regulatory framework in balancing markets are presented whereas Chapter 5 focuses on the case study of our thesis. The operation, the aging model, the different bidding strategies are shown and the impact of availability and PCR price evolution on revenues is analyzed in order to assess the economic feasibility of such investments.

Keywords

Battery Energy Storage System, Primary Control Reserve, Frequency Control Reserve, Ancillary Services, German Energy Market

1. Introduction

European Union energy policy calls for at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 32% share for renewable energy and at least 32.5% improvement in energy efficiency by 2030 [1]. The targets for 2050 are more ambitious and the scenarios presented in the Energy Roadmap 2050 [2] highlight the importance of a decarbonized energy system, with conventional fossil units being gradually replaced by renewable energy sources.

Hence, the integration of renewable energy sources in the distribution systems poses new challenges to the electrical power systems. The electricity generation based on wind and solar is fluctuating and intermittent as they depend on the local weather conditions, which makes their electrical power provision uncertain. These fast and short time fluctuations can significantly influence the stability of the networks, with rotor- angle, voltage and frequency stability being the major issues resulting from the high penetration of RES.

The above challenges highlight the need of flexibility within the electrical power systems. In this direction, battery energy storage systems aim to guarantee the stability of the energy power systems by participating in energy production and contributing to the provision ancillary services. The participation of BESS in the power networks enables a more efficient use of the existing infrastructure for electricity supply and energy resources. Energy storage systems contribute to electricity generation and supply, support the more efficient operation of conventional generation units, provide grid operational support, maintain power quality plus reliability, and support the further integration of fluctuating renewable-based generation [3].

2. Battery Energy Storage Systems

2.1 Introduction

Energy storage systems (ESS) can be applied to any of the five major subsystems in the electric power system: generation, transmission, substations, distribution, and final consumers [3]. At the generation level, ESS can ensure the provision of additional energy when generators are operating at capacity or when renewables cannot ensure enough production. At the transmission level, ESS can contribute to congestion management by providing additional energy at the receiving end of a congested line. At the transformer level, ESS can store energy when the transformer is not operating at capacity and feed it into the network when it is needed. Furthermore, ESS can allow the consumer to store energy when excess capacity or low cost electricity is available, thus enabling their active participation in the distribution grid [3].

There are many benefits by integrating energy storage systems into the electricity grid, such as:

- facilitating the balancing of electricity supply and load at lower cost by providing time-shift energy delivery,
- supplying capacity giving added value to investment deferral
- providing grid operational support to mitigate rotor- angle, voltage and frequency instability
- ensuring power quality and reliability by providing energy to the grid with fast response times, and
- allowing integration of renewable energy sources by smoothing their intermittent energy provision [3].

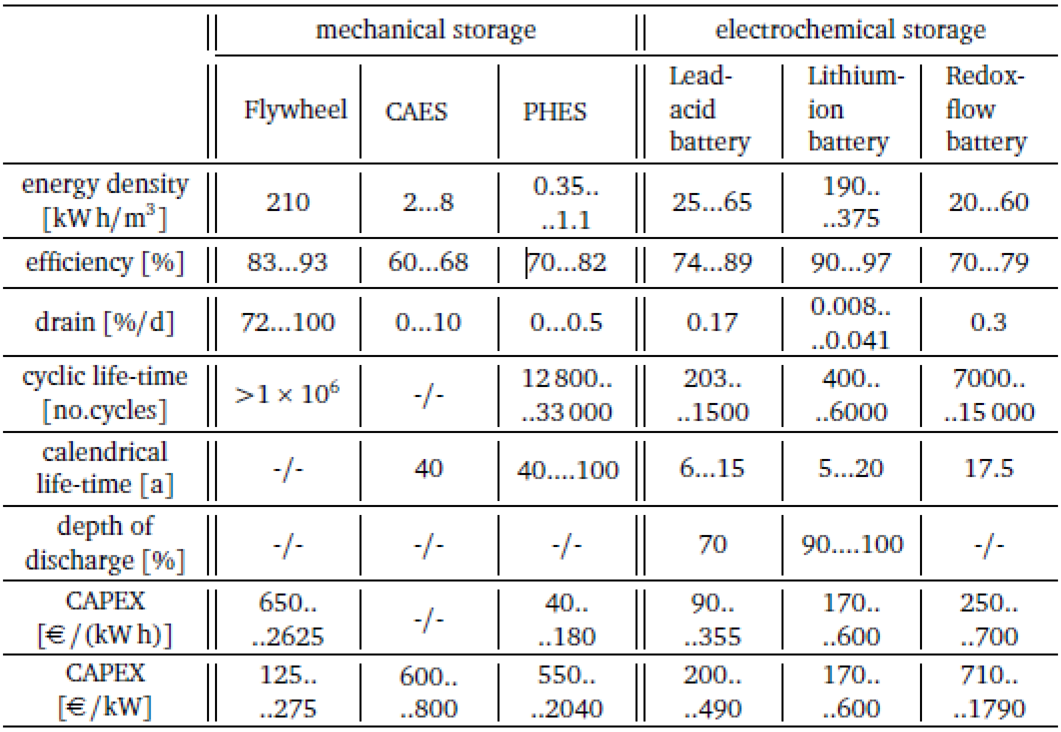
2.2 BESS Technologies

There is a wide range of energy storage technologies integrated into today's electrical power systems. They can be classified into five major types with regard to the nature of stored energy, which represents the available wide range of storage technologies:

- mechanical storage, like pumped hydroelectric, compressed air, or kinetic storage,
- chemical storage, such as hydrogen or synthetic natural gas,
- electrochemical storage, such as secondary or flow batteries,
- electrical storage, like capacitors and superconductors, and
- thermal storage, such as molten-salt [3].

In the following table [4], the most common energy storage technologies are presented.

Table 1: Characteristics of common energy storage technologies [4]



	mechanical storage			electrochemical storage		
	Flywheel	CAES	PHES	Lead-acid battery	Lithium-ion battery	Redox-flow battery
energy density [kW h/m^3]	210	2...8	0.35.. ..1.1	25...65	190.. ..375	20...60
efficiency [%]	83...93	60...68	70...82	74...89	90...97	70...79
drain [%/d]	72...100	0...10	0...0.5	0.17	0.008.. ..0.041	0.3
cyclic life-time [no.cycles]	$>1\times10^6$	-/-	12 800.. ..33 000	203.. ..1500	400.. ..6000	7000.. ..15 000
calendrical life-time [a]	-/-	40	40....100	6...15	5...20	17.5
depth of discharge [%]	-/-	-/-	-/-	70	90....100	-/-
CAPEX [€/(kW h)]	650.. ..2625	-/-	40.. ..180	90.. ..355	170.. ..600	250.. ..700
CAPEX [€/kW]	125.. ..275	600.. ..800	550.. ..2040	200.. ..490	170.. ..600	710.. ..1790

Flywheel energy storage system is based on the operation of electric motors in order to drive the flywheel to rotate at a high speed and transform the electrical power into mechanical power. The flywheel system operates in the high vacuum environment. They are characterized by no friction loss, small wind resistance, long life, and no impact on the environment. These systems operate in the high vacuum environment. Its disadvantages include low energy density and high cost of ensuring the system's security [5].

Compressed air energy storage (CAES) is based around the gas turbine cycle. Surplus power is used to compress air with the use of a rotary compressor. The storage is done in an underground chamber. Air is released from the chamber and passed through an air turbine that generates electricity from the flow of high pressure air. To increase power production, the plant can be boosted by burning natural gas in the high pressure air before it enters the air turbine [6].

The pumped hydro energy storage (PHES) is a well-established technology for utility-scale electricity storage and has been used since 1890s. It is based in hydro power, hence ensuring flexibility and storage capacity able to ensure grid stability and to support the operation of other intermittent renewable energy sources. PHES is most suitable for small autonomous grids and massive energy storage [7].

However, lead-acid and lithium-ion batteries are the main battery technologies used in Germany. Lead-Acid batteries are used more than 100 years in both mobile and stationary applications, such as starter batteries, traction of vehicles, emergency electricity supply, off-grid electric power systems, etc. Nowadays, they are the most commonly used battery storage technology, achieving cycling efficiencies of around 74% to 89% at low cost [3, 4]. Lead–acid batteries contain metallic lead, lead dioxide, lead sulfate and sulfuric acid. They consist of two plates of electrodes, that are suspended in electrolyte and detached by a separator, called flooded lead-acid cell. The negative electrodes are made of metallic lead containing also minor fractions of e.g., calcium, tin, antimony. The positive electrodes are made of lead oxides in various compositions. Lead and lead oxides are categorized hazardous heavy metal materials, however, under normal battery operation, no chemical components can escape the enclosure, but during the recycling of spent batteries, special attention needs to be paid for avoiding hazardous chemical exposure to the production staff [4, 8]. If the charging or discharging power gets too high, storable energy is wasted and gases emerge, decreasing the available capacity of the battery. Hence, lead-acid batteries require suitable ventilation. Also, flooded lead-acid cells need water topping, which increases the maintenance costs, but in general, they have low costs and a high life-time, especially at high temperatures [4].

Lithium-ion batteries are one of the most popular batteries due their ability to meet new challenges, including decreasing costs [4]. They are used both in mobility applications, such as electric vehicles, and for fast requiring time-shift applications in power networks, like peak-shaving, PV-smoothing, etc. [3]. Lead-acid batteries are usually replaced by lithium-ion batteries, which are lighter and have better energy density and efficiency. Lithium-ion batteries consist of a positive electrode made of lithium metal oxide or phosphate, a negative electrode made of graphite and a separator, surrounded by an electrolyte. Lithium salts and additives are dissolved within the electrolyte to improve their lifetime. The increasing demand for lithium-ion batteries led to improvements regarding energy density, operating temperature, safety, durability, charging time, output power, and costs. Thus, there are many different lithium-ion cell technologies available today, with different electrode materials according to their application [4]. The different commercial types of Lithium-ion batteries present particular technical specifications, like thermal runaway set point, but the electrochemical principle is the same for all. The technical and commercial classification of the type of Lithium-ion batteries is based on the type of the cathode, so we could have:

- Lithium Cobalt Oxide or LCO ($LiCoO2$)
- Lithium Manganese Oxide or LMO ($LiMn2O4$);
- Lithium Nickel Cobalt aluminum Oxide or NCA ($LiNiCoAlO2$);
- Lithium Nickel Manganese Cobalt Oxide or MNC ($LiNiMnCoO2$);
- Lithium Iron Phosphate or LFP ($LiFePO4$).

A comparison between lead-acid and lithium ion batteries for stationary storage in off-grid energy systems presented in [9], indicates that lithium-ion have higher efficiency, longer lifetimes and faster charging capabilities in comparison to lead-acid. However, in low temperature conditions, lead acid batteries are proved to be safer [9]. In any case, the choice should be done according to the particular application, considering also a cost analysis between the alternatives.

2.3 Lithium-ion ESS Main Equipment

A typical lithium-ion BESS includes:

a) Cells grouped in modules and racks.
b) Electronic management system for operation of the cells.
c) Inverters, power transformers.

d) Electrical and automation board to interface the BESS with the external grid, plant SCADA and remote control station.
e) Cable and cable ways to connect the equipment and auxiliary systems like HVAC, lighting system, video surveillance system and fire suppression system.

A battery cell is the basic functional electrochemical unit containing an assembly of electrodes, electrolyte, separators, container and terminals. It is a source of electrical energy by direct conversion of chemical energy. A single cell or a group of cells connected together electrically in series, in parallel, or a combination of both forms a battery module. A battery module is capable of charging, discharging and storing energy electrochemically. Respectively, a battery rack is a stack of multiple battery modules, connected in series to develop a high DC voltage.

Below are presented the three main systems to monitor and control a BESS, the Battery Management Control System (BMS), the Power Conversion System (PCS) and the Storage Management System (SMS).

The Battery Management Control System (BMS), manages and monitors the battery pack storage. Its main functions focus on:

- Electrical Protection (overcurrent/overvoltage), as a safety-related battery protection action.
- Thermal Protection, controlling cell temperatures and its environment.
- Accurate cell balancing, as functionality in the service of energy storage performance optimization.

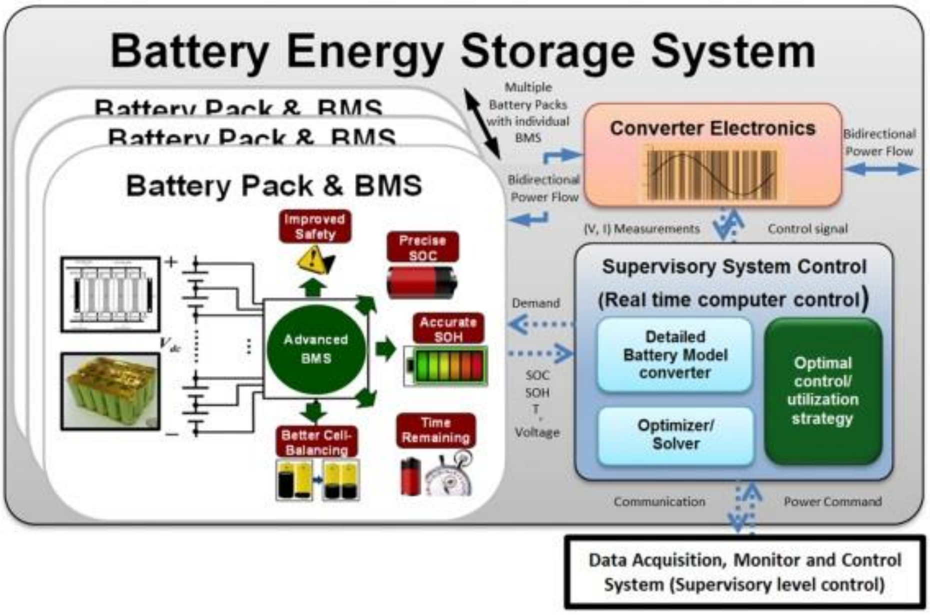


Figure 1: Schematic for the implementation of a battery pack and BMS into a BESS [31]

The Power Conversion System (PCS) is the interface between the DC battery system and the AC system. It is responsible for the charging and discharging of the battery. PCS may consist of one or more parallel units, as a bi-directional inverter with four quadrant operation, capable to adjust the output voltage & frequency to suit the grid condition. The PCS shall be capable of automatic and unattended operation, such as self-protection, synchronizing and paralleling with the grid, etc.

The Storage Management System (or System Supervisory Control – SSC) is the main control component that manages the Power Conversion System and the Battery Management System. Its main functions are:

- To interface the BESS with the external systems
- To collect all the information coming from both PCS and BMS (operating limits, status, warnings and alarms, etc.)
- To provide the power and services requests through the PCS and by exploiting the data acquired from the BMS
- To interface the auxiliary components and apply operating set points coming from external controllers (signals form the market)
- To optimize use of the batteries with the aim to maximize their lifetime and to reduce the energy losses

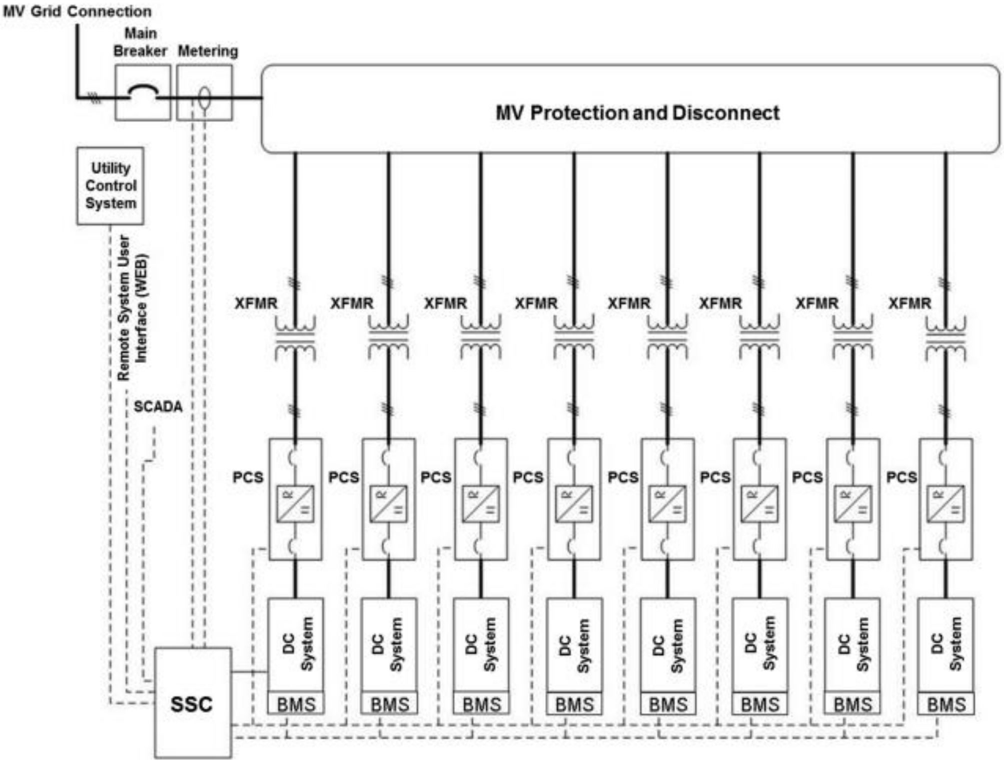


Figure 2: Simplified illustration of GSS architecture, including several independent modules which all operate under BMS and SSC control [31]

The above components are usually placed indoors, inside shelters like ISO metal containers or isolated building or room inside building.

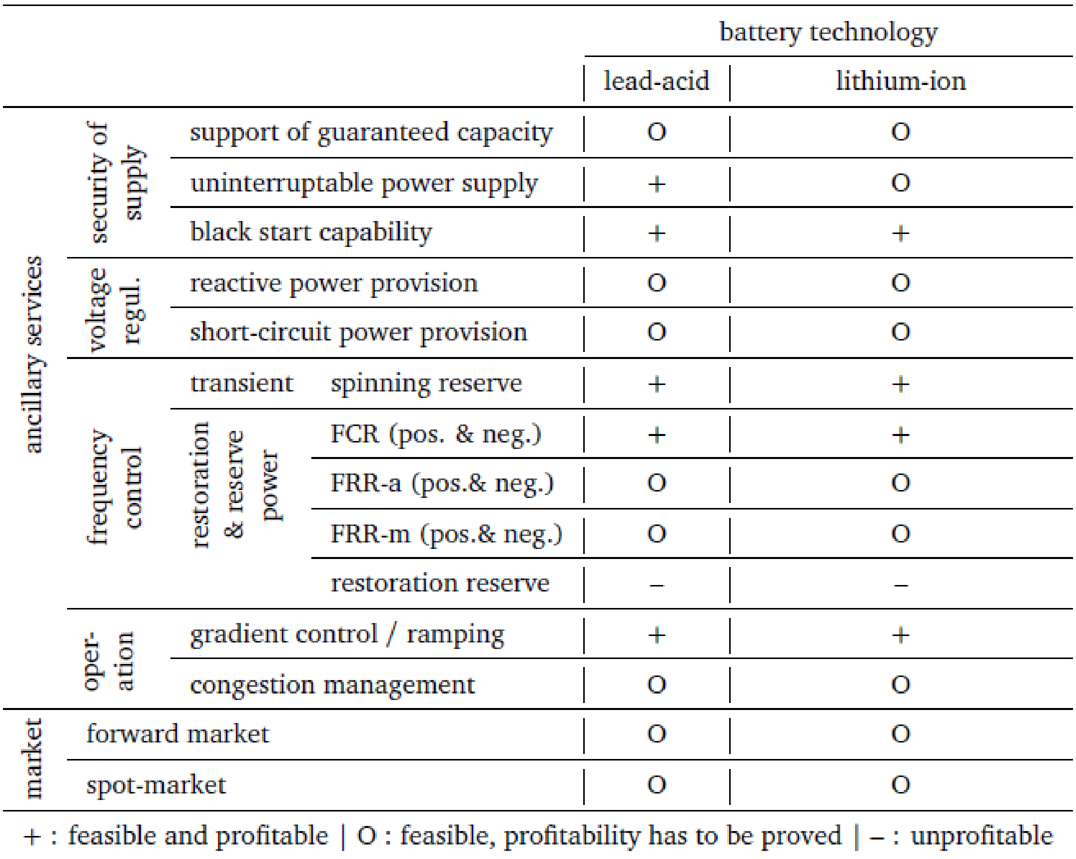
2.4 Application of BESS in Power Systems

Battery energy storage systems can be found as stand-alone power supplies or together with wind or photovoltaic plants in order to increase the full-load hours of the renewables. They can either participate in the energy market, providing energy as any other generation unit, or provide ancillary services. It is a matter of strategy if a BESS system will serve both of the above scopes.

The integration of battery energy storage systems in power systems offers enormous benefits. BESS are able to support distribution system operators to overcome the challenges posed by increasing penetration of distributed generation. They can improve power quality, lower energy costs, reduce emissions and defer investments in transmission and distribution networks. Therefore, BESS can lessen the need for emergency reserves of energy, increase grid efficiency, reliability, as well as flexibility [10]. BESS can be found as stand-alone power supplies or operate together with wind or photovoltaic plants in order to increase the full-load hours of the renewables. They can either participate in the energy market, providing energy as any other generation unit, or provide ancillary services. It is a matter of strategy if a BESS system will serve both of the above scopes.

In the following table, the technical feasibility and the economical profitability of lead-acid and lithium-ion batteries is presented [11]. It is obvious that ancillary services is the main purpose that batteries can serve both technically and also with economic benefits. However, the renumeration of additional ancillary services (except for frequency control reserve) is still an open [11].

Table 2: Comparison between technical feasibility and economical profitability of lead-acid and lithium-ion batteries [11]



				battery technology	
				lead-acid	lithium-ion
ancillary services	security of supply	support of guaranteed capacity		O	O
		uninterruptable power supply		+	O
		black start capability		+	+
	voltage regul.	reactive power provision		O	O
		short-circuit power provision		O	O
	frequency control	transient	spinning reserve	+	+
		restoration & reserve power	FCR (pos. & neg.)	+	+
			FRR-a (pos.& neg.)	O	O
			FRR-m (pos.& neg.)	O	O
			restoration reserve	–	–
	oper-ation	gradient control / ramping		+	+
		congestion management		O	O
market	forward market			O	O
	spot-market			O	O

+ : feasible and profitable | O : feasible, profitability has to be proved | – : unprofitable

Below are presented some of the most common applications of BESS in power systems.

- Renewable integration

One of the most important applications for BESS in a power system is to support the intermittent production of renewable energy sources. Also, BESS improves power system reliability when this is affected by RES and is seen as an tool to smooth wind or solar power generation fluctuations. Especially for wind plants, BESS has proved the most popular mature technology to support them [12]. Hence, renewable sources have increased the need for storage in power systems [10].

- Frequency regulation – Primary Control Reserve (FCR)

The great advantage of BESS compared to other technologies is the ability to response fast and precisely to frequency deviations, making it an optimal technical solution for primary control provision [13]. Hence, BESS is evaluated as an effective regulation resource to respond immediately to frequency deviation [12]. However, it is important to ensure the interoperability of the BESS for primary control provision under an adequate charge level management because of the limitation of the lifetime of battery packs [10].

- Reliability

BESS can be used to react immediately after a contingency, thus helping to maintain the stability of the power networks. It is seen as a tool to post-contingency corrective control actions to keep the balance of load generation. BESS can provide energy immediately when needed to mitigate the impact of natural disasters, or to support distribution network isolated areas [12].

- Congestion management

The ability of BESS to charge and discharge (inject or absorb energy) makes it a critical asset in congestion management. As the increasing penetration of RES in the networks often leads to overvoltage and reverse power flows, BESS can alleviate the network contingencies and reduce the risk of consequences of overloaded networks in peak hours [12].

- Network upgrade deferral

Investment deferral is an important characteristic of today's active transmission and distribution networks. The uncertainty of demand and the quick technological changes call for delays in investment decisions in order to be able to exploit real option analysis. BESS is presented as an alternative to ensure a proper integration of today's energy demand instead of immediately choosing grid reinforcement to increase the line's capacity [12].

- Power quality

BESS is suitable to enhance the power quality by smoothing voltage variations. High RES penetration in power networks as well as low demand lead to overvoltage, which BESS can diminish. BESS can be a good emergency power supply extreme case scenarios, by absorbing or injecting reactive power and enabling the real power flow when required [12].

- Voltage regulation

The integration of BESS in power systems can mitigate voltage deviations and encourage the integration of more renewable energy sources. BESS can improve the voltage profile in a network by regulating active and reactive power [12].

- Spinning Reserve

Spinning reserve is defined as unloaded generation that is rotating in synchronism with a utility-grid and is ready to serve additional load demand [14]. It requires response time from seconds up to 10 minutes. BESS quick time responses make it an ideal system able to provide spinning reserve in a power system. Based on the frequency deviations, BESS is charged when the frequency values are above a superior limit and discharged when frequency values are below a predefined limit [12].

3. Balancing Market Services

3.1 Introduction

A balancing market consists of three main phases: balance planning, balancing service provision, and balance settlement. The actors involved in the balancing market are the System Operator, the Balancing Service Providers (BSPs) and the Balance Responsible Parties (BRPs). At first, BRPs submit energy schedules to the system operator, declaring the planned energy generation and consumption for each Schedule Time Unit (STU) within the specified time of delivery (balance planning phase). Then, BSPs submit balancing service bids to the system operator, which are procured in price order to ensure the balance of the system (balancing service provision phase). Finally, energy imbalances are settled (balance settlement phase) [15]. The figure below [15] presents the basic structure of the balancing market.

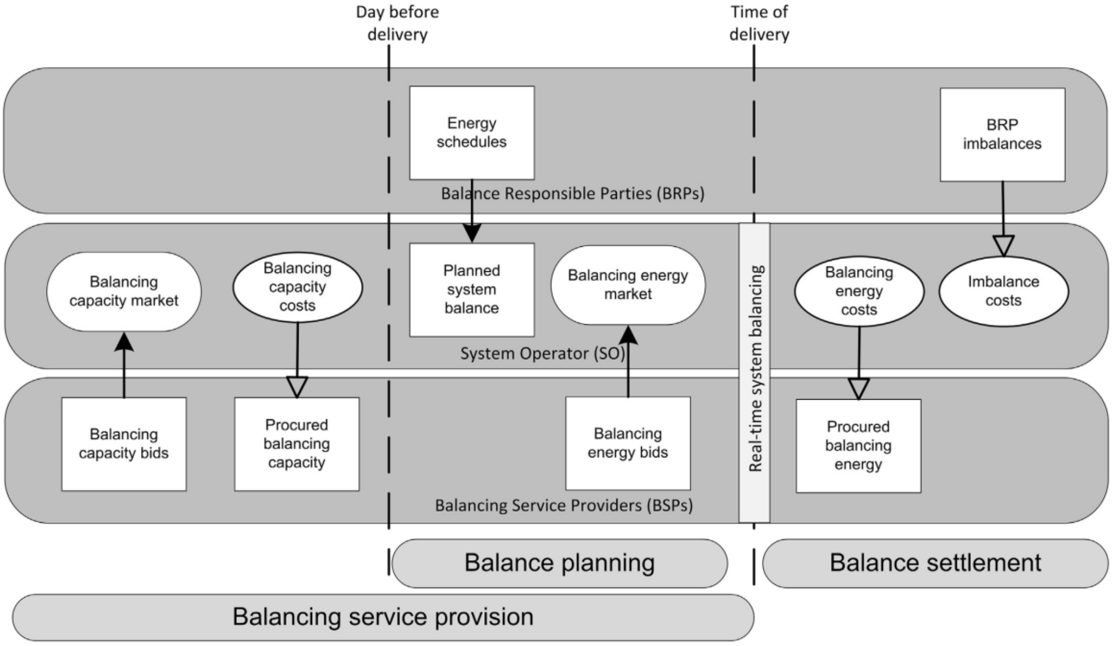


Figure 3: Basic Structure of Balancing Market [15]

Balancing services are within TSO's responsibility. With the term 'balancing', we refer to "all actions and processes, on all timelines, through which TSOs ensure, in a continuous way, the maintenance of system frequency within a predefined stability range" [16]. However, the products used for balancing services can also be used for DSO services as well. Hence, the need for cooperation and coordination between TSOs and DSOs is crucial, so that the activation of a service by the TSO does not have a negative impact for the DSO [17]. Below are described the main balancing market services across Europe.

3.2 Frequency Containment Reserves (FCR)

Frequency containment aims at stabilizing the frequency at a target value and avoid blackouts in the event of frequency deviation after disturbances in the high-voltage grid [17,18]. It refers to the automatic and proportional response of the available active power reserves to maintain frequency within acceptable limits after the occurrence of an imbalance. In the past, in most countries, generators were the main providers of FCR, however nowadays energy storage systems and demand-response aggregators start playing an important role in FCR services. The importance of FCR services is highlighted by the obligation of the Network Code for the TSOs to develop a common European platform for the exchange of balancing energy from FCR [17]. In this direction, the Austrian, Belgian, Dutch, French, German and Swiss TSOs participate in a common market for procurement and exchange of FCR (FCR Cooperation) [19].

In some countries the grid user has no obligation to offer the reserve and may voluntarily participate in the market through an auction, a market platform etc. The offer can be customized in terms of volume and timeframe and or he can bid at a specific price. In most cases, only the reservation of FRC is renumerated. When the activation of FCR is not remunerated, FCR is symmetric (offering fast upwards and downward energy), as activations in both directions would result to cancelling out payments [17].

3.3 Automatic Frequency Restoration Reserve (aFRR)

Automatic Frequency Restoration reserve also referred to as Secondary Control Reserve (SCR) aims to support FCR and restore the frequency at a steady-state value by activating automatic control devices within a timeframe of 5 minutes [20]. These devices are designed to reduce the Frequency Restoration Control Error (FRCE) to zero. The full activation time can be divided into the preparation and the ramping period. [17]. The European project PICASSO [21] aims to design, implement and finally operate a platform for the exchange of balancing energy from frequency restoration reserves with automatic activation.

Settlement rules differ between countries. In France and Denmark the prices are regulated whereas in Germany and most of central Europe the scheme “pay as bid” is applied. On the other hand, Nordic countries and Iberian peninsula follow the marginal pricing [17]. Differences exist also regarding the tendering periods. In some countries there are weekly, monthly or even yearly tenders. Moreover, the energy and capacity procurement can be combined in one auction (explicit), or only energy bids exists (implicit) [17].

3.4 Manual Frequency Restoration Reserve (mFRR)

Manual Frequency Restoration Reserve (mFRR) aims to restore system frequency by a manual change in the operation set-points of the active power reserves of a synchronous area, mainly by re-scheduling. This is achieved by the obligation of TSOs and DSOs to cooperate in order to facilitate and enable the delivery mFRR by units located in the distribution systems [17]. Hence, the European TSOs have started working on the design of an mFRR platform, called MARI [17]. For the standard mFRR product, a linear ramp of 10 minutes for the cross-border exchange, with full activation time set at 12.5 minutes maximum will be used [17]. Some countries like France, Germany, UK, etc. enable load participation in mFRR whereas others additionally provide for pump storage and batteries participation. However, there are countries like Romania and Greece that allow only generation to provide mFRR.

3.5 Replacement reserves (RR)

The process of replacing the activated FRR is called replacement reserve (RR). The replacement reserve process is activated in semi-automatic or manual way in the disturbed local frequency control area, using the active power reserves available to restore or support the required level of FRR to be prepared for additional system imbalances, including generation reserves. TSOs and DSOs cooperation for the facilitation of the delivery of mFRR, a European platform for the exchange of balancing energy from RR will be developed. The full activation time of the RR standard product will be 30 minutes whereas the ramping period can be from 0 to 30 minutes [17].

3.6 Fast frequency reserves (FFR)

Fast Frequency Response (FFR) refers to any type of rapid active power increase or decrease by generation or load, aiming at correcting imbalances between supply and demand in a timeframe of 2 seconds. The high penetration of RES in the power networks and the reduction of rotating machines makes necessary the need of available sources of inertia in the system and hence the necessity of new fast services such as fast-frequency-control and inertial response. Such services can be operated by generation/load units based on power electronic interfaces, capable of adapting their power output to reduce further deviations of frequency [17]. The timeframe for the service activation is defined as 2 seconds (from 49,6 Hz), with a duration of 30 seconds. In some countries, the capability of offering such services is renumerated as “pay as bid”, whereas the reserves are to be paid the price of the last bid accepted (marginal pricing) [17].

3.7 Ramp control

Ramp control aims to ensure system stability by responding to variations in production and demand, with an 8-hour ramping period with 8 hours of maintaining level of production. Ramp control service is mainly related to ramping margin. Ramping margin service introduces a new product, a ramping tool for control center, which is in creation phase and aims to enable grid controllers to accurately schedule and dispatch the ramping margin services, and handle changes in production and demand [17].

3.8 Smoothed production

Generation schedule smoothing uses an algorithm to detect imbalances several hours in advance of real-time operation and suggests schedule adjustments by shifting part of production up to 30 minutes [17]. Although it has similarities to mFRR, it focuses more on planning. Smoothing production service should not interfere with other ancillary services, as production plans and plans for production smoothing should be independent. Production smoothing service is included as an adjustment in the balance settlement [17]. In some countries (Finland, Sweden and Norway), quarterly adjustment of production is already applied. TSOs are mainly concerned for this service, although in future also DSOs could use similar services for RES and DER connected to the distribution grids [17].

3.9 BRP portfolio balancing

Balancing Responsible Parties (BRP) have a fundamental role in the electricity market. BRP is responsible for balancing its own position, by forecasting the energy consumed in his portfolio and the required amount of energy to match that consumption, either produced by generation units in the BPR's portfolio or imported or bought on the market. By balancing his own position, the BRP contributes to the balance of the electricity system. Currently, in order to balance their portfolios' needs, BRPs utilize several different markets and bilateral. The balancing takes place intra-day, up to 2 hours ahead of the operation interval [17].

4. German PCR Market

4.1 Introduction

As our case study is a BESS plant in Germany, in the following sections we will analyze the electrical power system and the regulatory framework of PCR market in Germany as well as the PCR price evolution.

4.2 Electrical Power System in Germany

The German Electrical Power System is divided into the following levels [11]:

- extra-high voltage level (380 kV, 220 kV, and High Voltage Direct Current (HVDC) transmission)
- high-voltage level (110 kV)
- medium-voltage level (20 kV and 10 kV)
- low voltage level (0.4 kV).

The transmission grid in Germany corresponds to the extra-high voltage level. All large generation units including renewable generation are interconnected to the extra-high voltage level and the electrical power is transmitted downstream to the 110 kV high-voltage level (primary distribution grids). A remarkable characteristic of the this system is that it ensures a synchronous operation of all operating generators by a tight coupling and a constant balancing between generation and demand not only during regular operation but also in case of unexpected events or sudden changes in demand [11].

Large consumers, such as industrial companies, are supplied directly from the transmission grid, but the majority of the electricity is transmitted to the downstream 110 kV primary distribution grids. The 110 kV level is subdivided into about 130 galvanically isolated grids with regional expansion, to limit the short-circuit power. The 110 kV high voltage grids transmit electricity over short distances to local load centers and medium industrial consumers [11].

The medium-voltage grids distribute the electricity to secondary substations in order to transmit electricity downstream to the low-voltage level. Low-voltage supplies final consumers like households and commercial consumers. Smaller generation units and renewables are connected to the medium and low voltage levels, increasing reversed power flows to upper grid levels [11].

The share of energy production by renewables increases continuously, as is shown in Figure 4 [22]. Especially the installed capacity of wind and solar plants has increased in the last years (see Fig. 3) [23]. However, their production depends on the local weather conditions, making uncertain the provision of electrical power. Energy storage systems can cover the intermittent production of renewables. Therefore, the integration of energy storage systems is more important than ever, in order not only to support the power grids but also to contribute to the integration of more renewables in the networks.

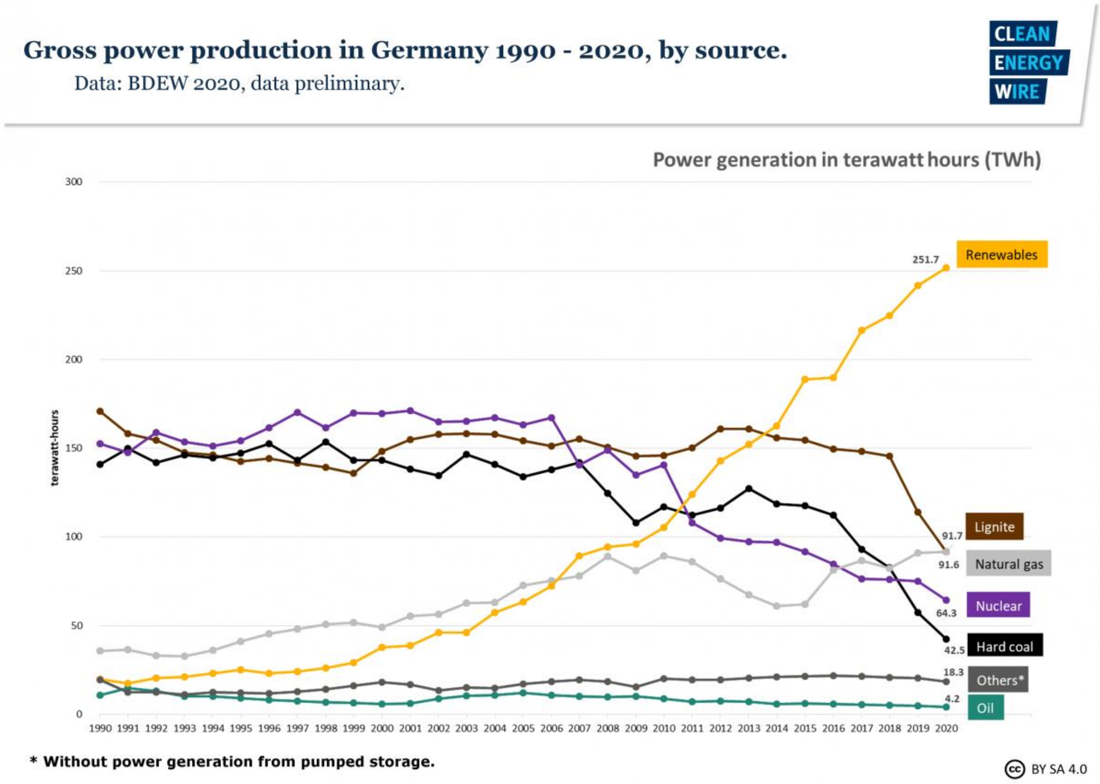


Figure 4: Gross power production in Germany by source [22]

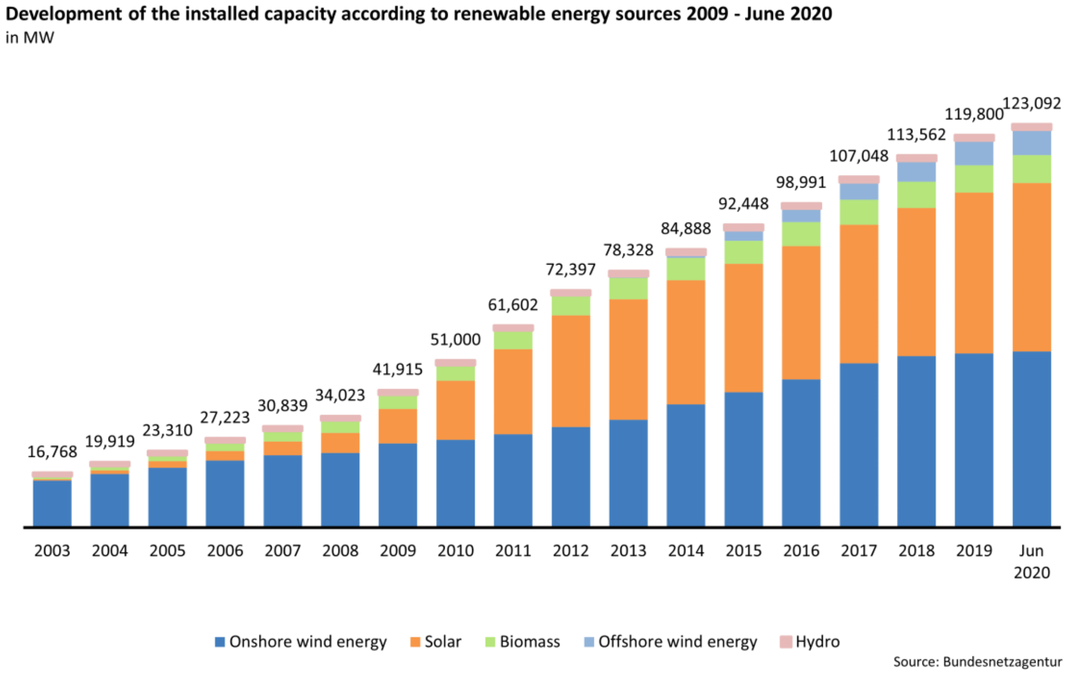


Figure 5: Development of the installed RES capacity in Germany [23]

Germany is one of the countries with the higher installed capacity of energy storage systems. In Figure 6 [24] are shown estimations for the cumulative battery capacity per country. It is depicted Germany and UK are and will be the leaders in distributed and utility scale storage in Europe [24].

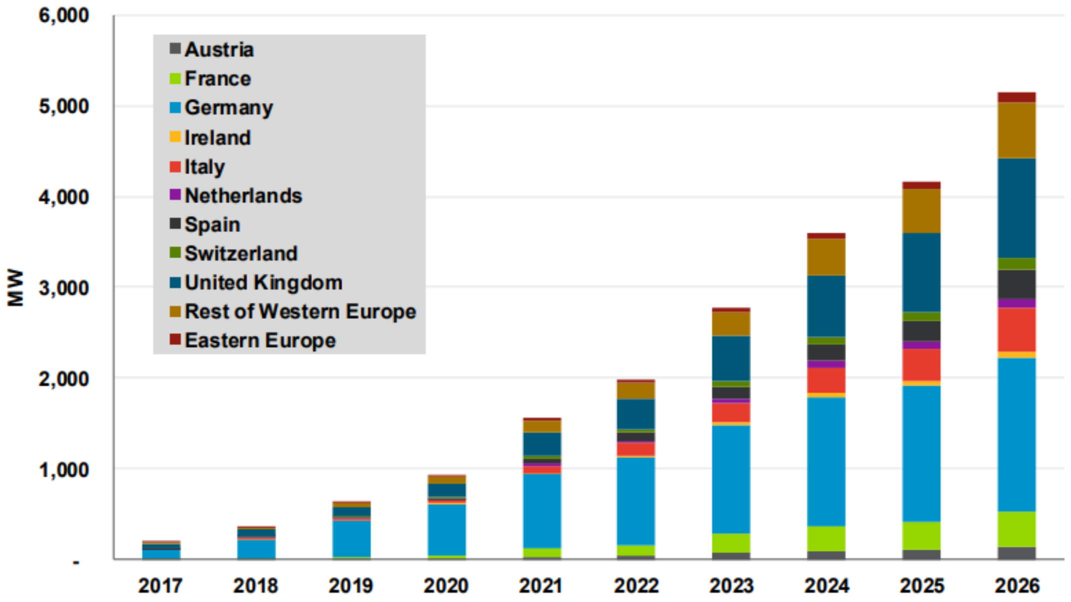


Figure 6: Annual Installed Distributed Energy Storage Power Capacity Additions in Europe [24]

4.3 Reserve Power Markets in Germany and Regulatory Framework for FCR provision

Ancillary services are defined as ancillary services that are necessary for the operation of transmission and distribution networks. These services are necessary for maintaining the system balance between production and demand and for ensuring frequency and voltage stability. In Germany there are four TSOs, which are responsible for the availability and supply of services, according to ENTSO-e guidelines and control mechanisms. For the performance of this task, the TSOs need different types of control reserve [25]:

- Frequency Containment Reserve (FCR)
- Frequency Restoration Reserve with automatic activation (aFRR)
- Frequency Restoration Reserve with manual activation (mFRR)

The technical complexity and the significant cost relevance of balancing services highlight the need for the imbalance price system to be subject of intensive regulation, such as general guidelines and laws, technical regulations, anti-trust law and regulatory requirements. Below is presented the regulatory framework for balancing in Germany. The complexity of the legal and regulatory framework make necessary the need of continuous development of procurement, provision and settlement[26].

- The guidelines of “System Operation” [27] and “Electricity Balancing” [28] entered into force as EU regulations in 2017. The System Operation guideline aims to create a legal framework for grid operation in order to facilitate electricity trading in Europe and ensure system security. The Electricity Balancing guideline establishes a functioning cross-zonal internal balancing energy market and aims to harmonize it with the national balancing markets. It contains direct requirements for the national balancing markets to be implemented as well as the internal EU balancing energy market [26].

- At national level, the legal framework deals with the balancing services and imbalance energy by defining both general principles and specific requirements for the market-based procurement and provision of balancing services. The specialized Electricity Grid Access Ordinance (StromNZV) provides detailed requirements for procurement, provision and settlement whereas the Renewable Energy Sources Act (EEG) specifies additional regulations on the participation of electricity generation plants in balancing markets based on renewable energies [26].
- In the Transmission Code of the German TSOs were initially described the prequalification of technical units that want to participate in the balancing markets. These were gradually replaced by revised prequalification conditions. Further developments of the prequalification requirements are agreed with the providers on a contractual basis, as can be found in the published model contracts. The obligations of the balancing responsible parties are regulated in balancing group contracts, provided as a template by the TSOs [26].
- The guideline on Electricity Balancing also impacts role of the German Federal Network Agency (Bundesnetzagentur – BNetzA) concerning
- The balancing market rules are defined by the European regulations and regulatory authority (Agency for the Cooperation of Energy Regulators – ACER). Hence, the Electricity Balancing guideline provides the TSOs the framework to make proposal for changes in the field of balancing. Proposals have to be first approved by national regulatory authorities. Since the entry into force of the Clean Energy Package (CEP), the regulatory authorities forward all applications submitted by the all TSOs directly to ACER.

Below are presented the most important regulations from Commission Regulation (EU) 2017/1485 concerning FCR power provision [11,32]:

- *Article 18, No.2:* A transmission system is in alert state, if “the TSO's reserve capacity is reduced by more than 20 % for longer than 30 minutes and there are no means to compensate for that reduction in real-time system operation”. Further conditions concern frequency: “the absolute value of the steady state power frequency deviation is not larger than the maximum steady state power frequency deviation and the absolute value of the steady state power frequency deviation has continuously exceeded 50% of the maximum steady state power frequency deviation for a time period longer than the alert state trigger time or the standard range of the power frequency for a time period longer than time to restore frequency”.
- *Article 154, No.2-No.3:* All TSOs of a synchronous area are allowed to specify additional requirements of the FCR power provision to ensure operational security. Additionally, the coordinator of a FCR power providing group has to enable ‘the monitoring of the FCR power activation of the units within’ its group.
- *Article 154, No.5-No.8:* Each unit or group providing FCR power must connect to only one control area respectively TSO. The contracted FCR power must be provided by automatically to frequency deviations. The provision of the contracted FCR power has to ‘begin as soon as possible after a frequency deviation’. In case of a frequency deviation equal or greater to 200 mHz, “at

least 50% of the full FCR capacity" have to be provided at the latest after 15s and 100% at the latest after 30s, where the activation of the full FCR power has to rise linearly from 15s to 30s. Each FCR provider has to make available the timestamped status indicating whether FCR power is provided or not, the timestamped active power data and the droop of the governor to the reserve connecting TSO for each of its units or groups.

- *Article 155, No.2 & No.6:* "A potential FCR provider shall demonstrate to the reserve connecting TSO that it complies with the technical and the additional requirements set out in Article 154 [...] by completing successfully the prequalification process". The re-assessment of the qualification for the provision of FCR power takes place "at least once every five years" or in the case of significant changes.
- *Article 156, No.4:* A provider of FCR power must guarantee the continuous provision of FCR during the whole contraction period with the exception of a forced outage of a unit.
- *Article 156, No.6-No.11:* To ensure operational security, the FCR power provided per unit should be limited to 5% of the FCR capacity required for the respective synchronous area. Such a unit that does not limit its capability to provide FCR shall provide FCR power "for as long as the frequency deviation persists". A unit "with an energy reservoir that limits its capability to provide FCR" must continuously be available during normal state. As of triggering the alert state and during the alert state, each provider must ensure that its units with limited energy reservoirs are able to fully activate FCR continuously for at least 15 min and in cases where not full activation is required, these units must be able to fully provide FCR power continuously for an equivalent length of time or for a period in the range of 15 min to 30 min defined by the reserve connecting TSO.
- *Article 156, No.13:* In case of units with energy reservoir limits, "the FCR provider shall ensure the recovery of the energy reservoirs as soon as possible, within 2 hours after the end of the alert state".

Hence, FCR power has to be delivered automatically by each market participant, either for the provision of positive and negative FCR power (symmetrical). The critical parameter for the provision of FCR power is the deviation of the power frequency to its nominal value of 50 Hz [32]. The figure below [33] represents the minimum required FCR power depending on the deviation of the power frequency from its nominal value of 50 Hz, which is expressed by equation below [11]:

$$P^{fcr} = \begin{cases} \mathrm{P}^{fcr}_{contr}, & \forall\, f < 49.8 \\ \mathrm{P}^{fcr}_{contr} * \dfrac{50 - f}{0.2}, & \forall\ 49.8 < f < 49.99 \ or\ 50.01 < f < 50.2 \\ -\mathrm{P}^{fcr}_{contr}, & \forall\, f > 49.8 \\ 0, & \text{else} \end{cases}$$

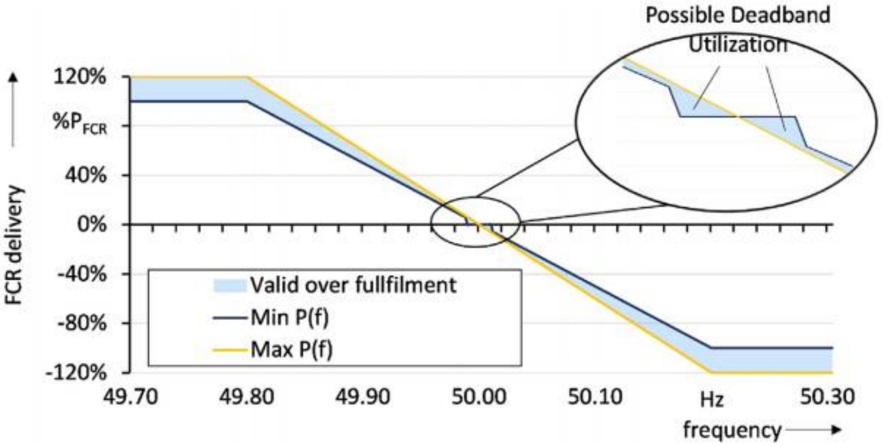


Figure 7: Minimum required frequency dependent provision of FCR power [33]

A deviation less than 50 Hz (f<50 Hz) means that electricity has to be injected into the grid, resulting in a request for the provision of positive FCR power. Respectively, deviation more than 50 Hz (f>50 Hz) means that less electricity has to be injected into the grid, resulting in a request for the provision of negative FCR power. The power can be up to 120% of the requirements according to the P (f) characteristic. However, an underfunding is not permitted. This degree of freedom can be used for memory management to selectively load or unload the memory when needed.

4.4 PCR Price Evolution in Germany

In the German market for balancing power, PCR is the product with the highest requirements in terms of reaction times and accuracy of regulation. As described previously, BESS are well suited for PCR provision as they offer short response times, precise controllability, high efficiencies and can be dimensioned flexibly. In the last years, the German PCR market has developed from a bilateral oligopolistic market to a more competitive market with approximately 700 MW of PCR procured in the German control area. TSOs from the Netherlands, Belgium, Switzerland, France and Austria also use the German auction platform to tender parts of their PCR demand, which results in an effectively bigger market size. In a later stage, the participation of the Danish TSO Energinet.dk and the Slovenian TSO Eles is planned [30]. According to the requirements, the maximum FCR export allowed is 30 % of the country's needed FCR, but never less than 100 MW [35].

Table 3 summarizes the product characteristics of PCR in Germany [29]. At first the call for tenders was weekly, but from 1st July 2019 the tender product became daily. The minimum lot size to bid is 1 MW symmetrically in upward and downward direction within the bidding period. Furthermore, only increments of 1 MW can be bid. The offers are sorted by the capacity price bid, so that the resulting Merit Order List up to the tendered amount is procured. There is a Pay-as-Bid procedure for the capacity price in place, whereas no additional compensation for activation is paid [26,27]. To participate in this market the technical unit or the portfolio comprising technical units have to pass the prequalification process in which the fulfillment of the technical requirements is audited by the connecting TSO. The most important technical requirements for FCR in Germany are listed below [30].

Table 3: Product characteristics of PCR in Germany

PCR market characteristics	
Tender product	Daily (with 4-hour products)
Minimum bid size	1 MW
Increment of bid size	1 MW
Call for tender capacity price [€/MW]	Merit-order
Remuneration	Pay-as-bid (capacity price)
Market size	approx. 1,400 MW (joint tender of German, Belgian, Dutch, French, Swiss and Austrian TSOs)

Since 1st December 2007, German transmission system operators (TSOs) have been meeting their Frequency Containment Reserves (FCR) requirements through shared calls for tenders. This has given TSOs a key role to play, as they had to conduct the prequalification procedure for the technical units to be marketed.

If a supplier markets technical units in several control areas, a framework agreement has to be concluded with each respective connecting TSO. A precondition for concluding such a framework agreement is a successful prequalification, whereby the prequalified capacity must at least equal the minimum lot size. The framework agreement is a precondition for taking part in a joint tender for FCR.

The TSO's shared Internet platform www.regelleistung.net has been used to implement the joint call for tenders since 1st December 2007. On this platform, calls for tenders are published, bids are processed, and bidders are informed whether their bids have been accepted or rejected.

When the respective calls for tenders are published, in accordance with Article 6 (2) of the Electricity Network Access Ordinance (StromNZV), the TSOs state the total requirement of the joint tenders. The call for tenders for FCR is 'symmetrical', meaning there is no separate call for tenders for positive FCR (additional power) and negative FCR (less power). The working day D-2 tender with a product period of one day launched on 1st July 2019 has been replaced by a daily FCR-tender with 4-hour products from 1st July 2020 [26].

In the figure below, the development of the average PCR capacity price from 2008 to 2020 is illustrated. From 2008 till 2011 prices fluctuated on a relatively high level between approx. 450 and 550 €/MW. In 2012, the average price dropped for the first time by 23 % to 400 €/MW. Prices recovered to a value of 529 €/MW in 2015. In 2016, the second price drop occurred, this time by 33 % to 357 €/MW. In 2020, the average price reached its lowest value, 171 €/MW [34,36]. The continuous drop in PCR capacity prices in the last five years is a critical signal for the investors in BESS, as they should adapt their bidding strategies to mitigate losses and ensure the sustainability of the investment.

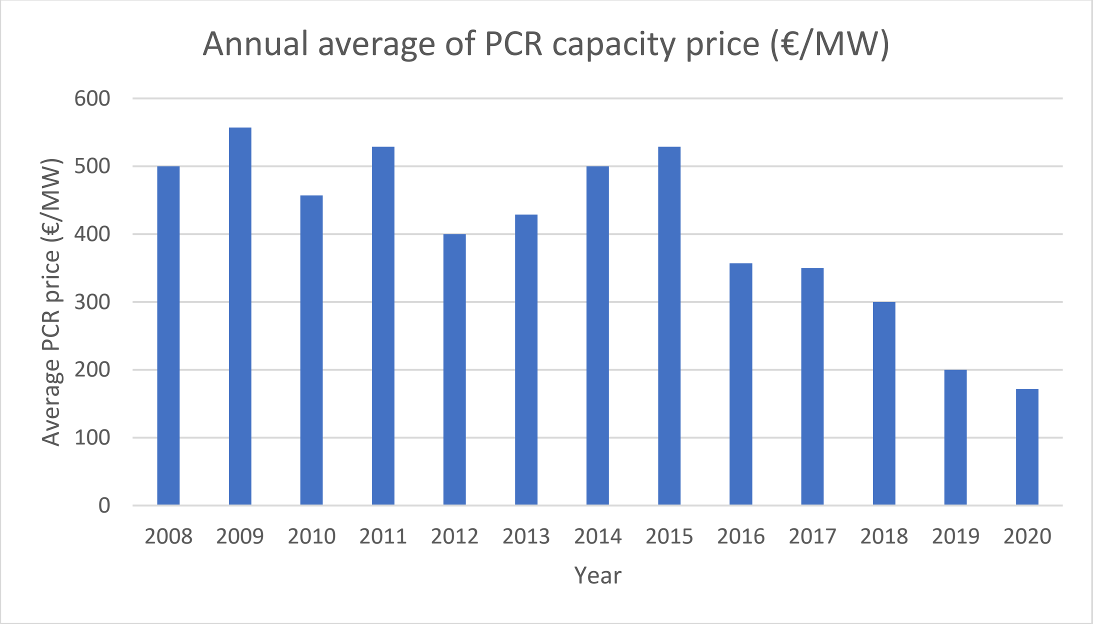


Figure 8: Annual average of PCR capacity price (€/MW) (own illustration based on [36])

5. Case Study

5.1 Description of the Case Study

In our study we will focus on a 22MW BESS in Germany, with installed battery capacity 33 MWh. It consists of 11 ESS, each of 2MW. Each ESS has 32 lithium-ion battery racks. Our site is connected to a 110/20 kV transformer bay. The primary application of the system is Grid Ancillary Services to the medium voltage grid. The technical layout of the system provides a multi-functional approach whereas the Lithium Ion batteries are capable of running continuously double power (2CP/2CP). This allows either increasing installed power or reducing installed capacity should the marked adapt to new regulations. Moreover, the Energy Management System operating the entire plant includes a rich library of ancillary services which allow shifting and adapting the use case of all single units to the most economical and optimized application. A single line diagram of a typical battery storage system is presented below:

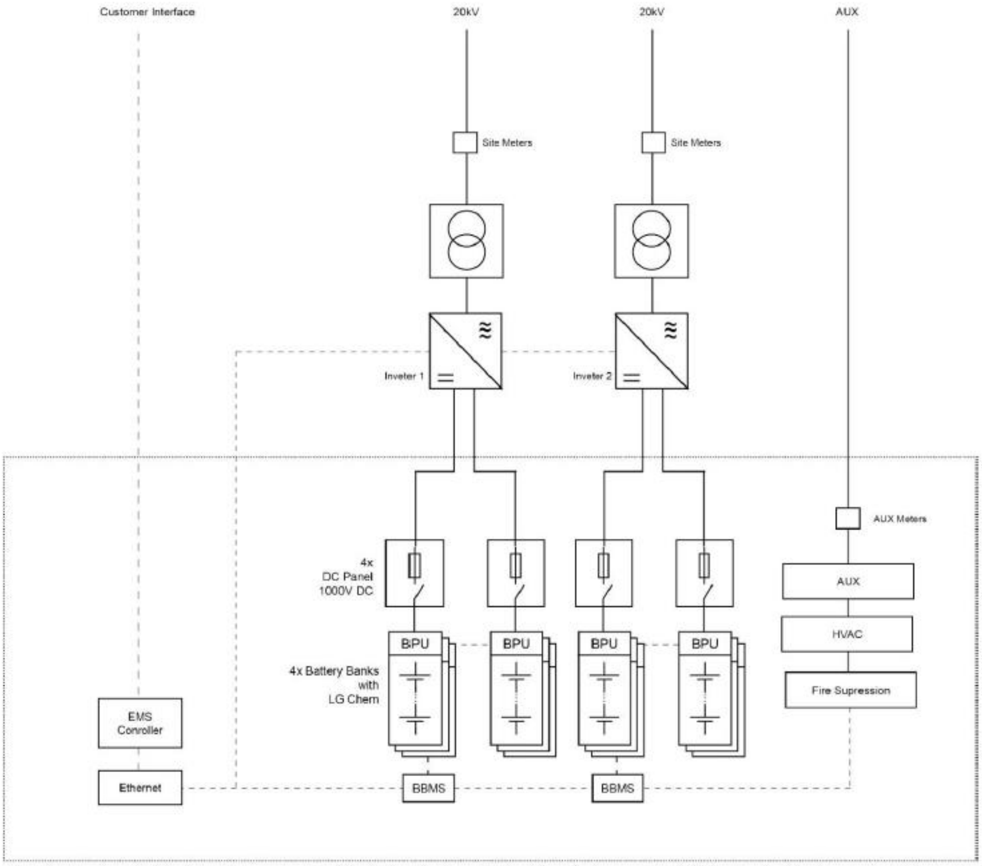


Figure 9: Typical Single Line Diagram of a Battery Energy Storage System

5.2 BESS operation

The batteries should always be ready to give full PCR power for 30 minutes. This is the "30 minutes rule". The following diagram shows the permissible working area of the battery plant in normal system operation depending on the ratio of power (MW) to capacity (MWh) as shown by the "30 minutes rule".

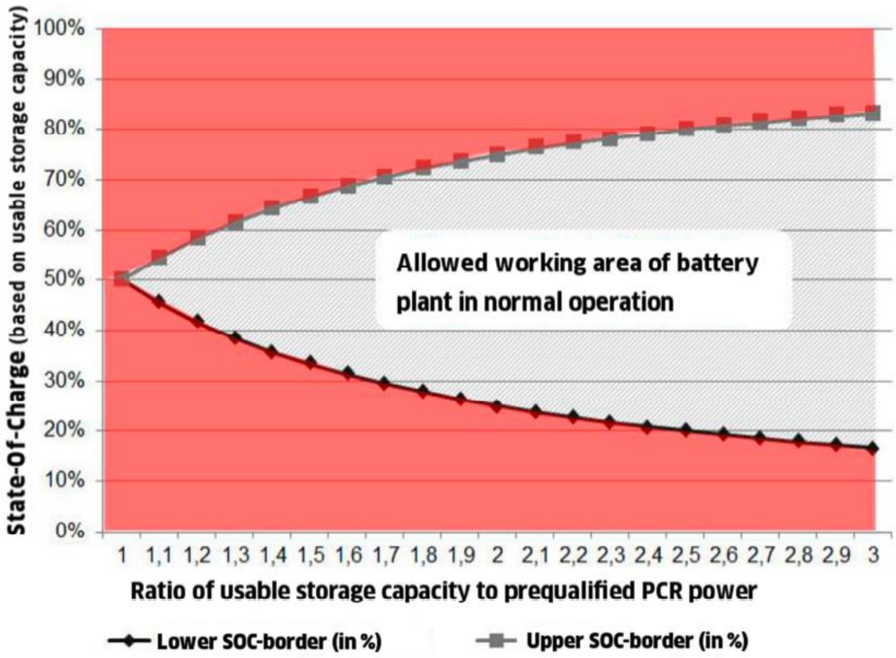


Figure 10: Permissible working area of the battery plant in normal system operation

For our case (22MW, 33MWh, ratio = 1.5), the limitation resulting from this rule is that the SOC should belong to the interval [37.5% / 62.5%] for normal system operation. We assume that our BESS is in normal system operation when the frequency deviation is below ± 50mHz, whereas is not in normal operation in one of the three following cases:

- Frequency deviation greater than ± 200mHz (i.e. frequency out of range [49.8 / 50.2]
- Frequency deviation greater than ± 100mHz for more than 5 minutes (i.e. the frequency is out of range [49.9 / 50.1]
- Frequency deviation greater than ± 50mHz for more than 15 minutes (i.e. frequency out of range [49.95 / 50.05]

When our BESS is not in normal system operation, it is possible to violate the limits we have set for the SOC, provided that it returns within the limits within two hours. In normal operation, we adjust the SOC as we prefer. In general, the average of the limits is a good value for an initial SOC value (i.e. 50%), however, in the majority of the cases the system requires the batteries to inject power to the network and rarely has a frequency above 50 Hz. Therefore, it is suggested to keep the SOC close to 55%. Respectively, in case the system shows a tendency that requires our batteries to absorb energy from the network, we could set as desired SOC around 45%. Below is presented a real time screenshot for the BESS operation.

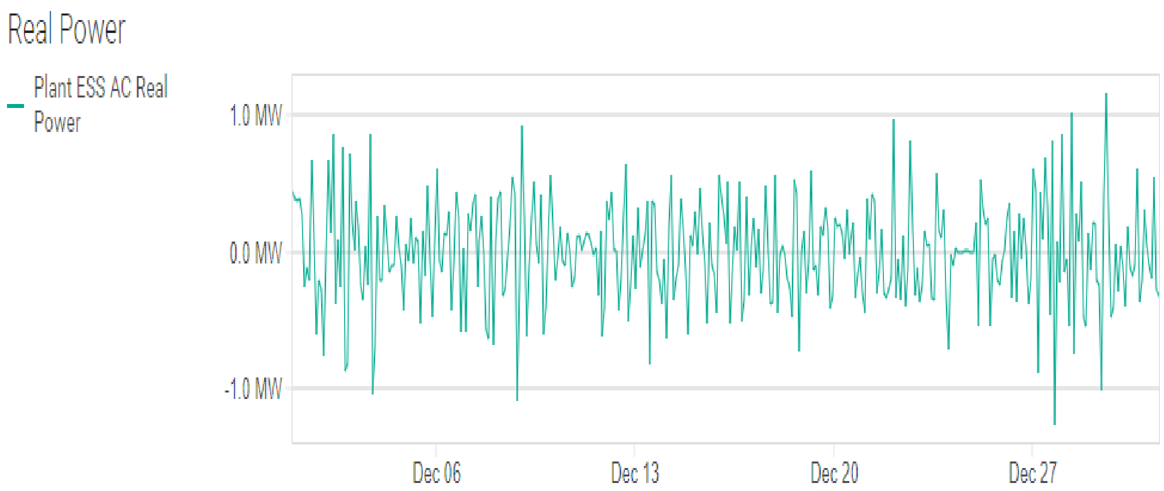


Figure 11: Real AC power of ESS

If the frequency variation is greater than ± 10mHz (i.e. the frequency is outside the limits [49.99 / 50.01], we are obliged to provide PCR services at any time and without time limit. When the frequency is within the limits, there is no need to provide PCR services. Then, we can either charge or discharge our batteries only and as long as the system-conforming behavior is ensured. Hence, we charge the batteries when the frequency is in the interval [50 / 50.01], and discharge them when the frequency is in the interval [49.99 / 50], in order to be close to the SOC chosen above.

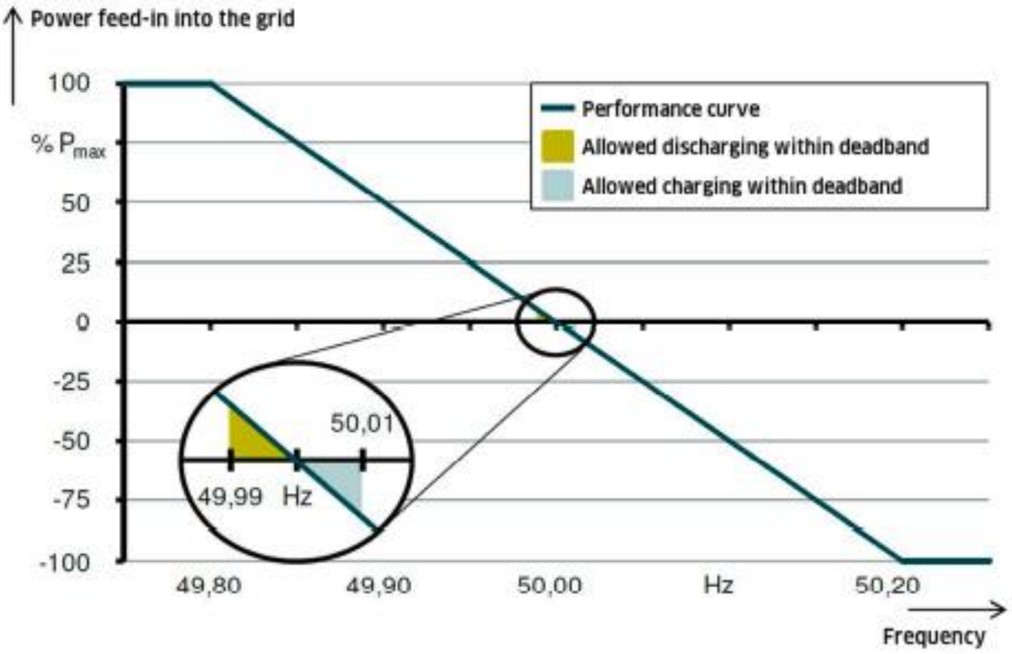


Figure 12: Allowed charging and discharging dead band

5.3 Aging model

In order to assess the investment of a BESS, a battery lifetime analysis is a crucial. Fast rate of fading of usable capacity reduces the operational lifetime of the battery system and equals to losses in expected revenues, as if requirements for prequalification are not met, the system will not be able to participate in the PCR market. Therefore, battery aging models taking into account both cyclic and calendar aging should be considered. The models usually consider the loss of available battery capacity due to cyclic stress at different depths of discharge (DoD), as well as the calendar aging over time at different SoCs [34].

The following figure shows the predicted 10-year degradation of our battery storage system based on the load profile for participation in the primary control market in Germany and on empirical data from reference installations (92% Depth of Discharge, 1CP / 1CP max). As in 10 years the State of Health of the BESS will be around 88%, a major replacement in battery cells will be required.

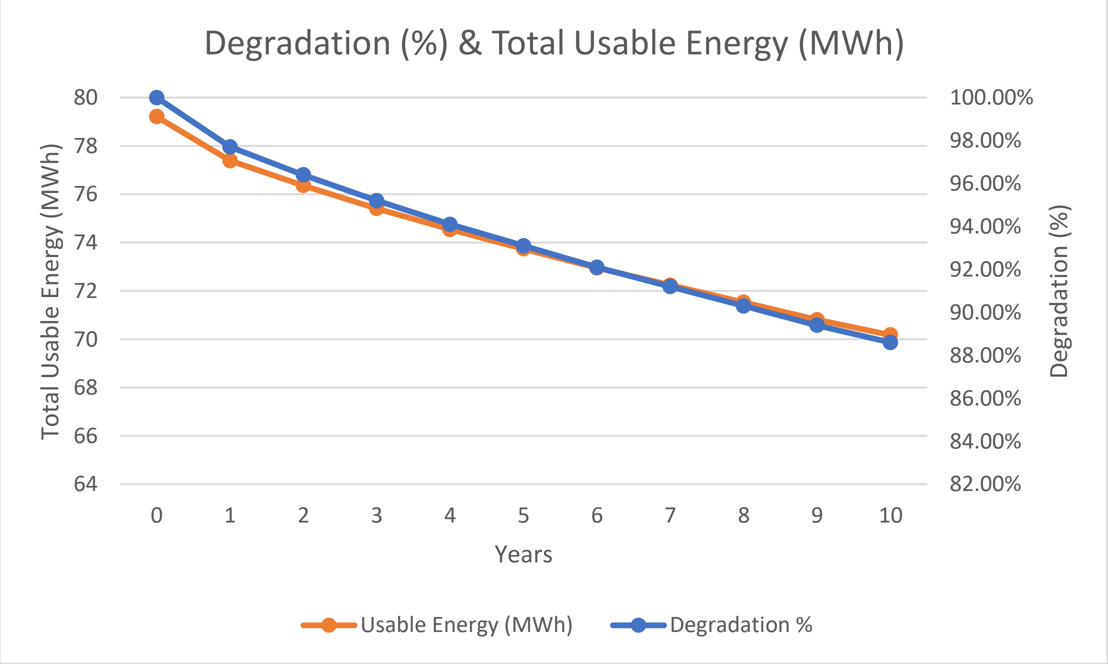


Figure 13: Degradation & Total Usable Energy in ten years operation

5.4 Bidding strategies

Bidding strategy is an important factor to be considered to calculate the associated lifetime expectancy of a BESS. Below are presented the different bidding strategies for a BESS on the PCR market, based on the PCR price expectations. The owners, in order to maximize their revenues, have the option either to participate in the PCR market or to offer the electricity generated in the Day-Ahead market. The PCR price forecast model was based on [34] and considers the PCR prices of the drawn bids in the previous tender, the technology portfolio of each PCR power supplier in Germany and the historic prices on the Day-Ahead (DA) market, according to the following equation:

$$P_{PCR} = \sum_{t=1}^{168} \begin{cases} P_{DA,t} - C_{var}, & if\ C_{var} \leq P_{DA,t} \\ \left(P_{DA,t} - C_{var}\right) * \dfrac{CAP_{min} + CAP_{PCR}}{CAP_{PCR}}, & if\ C_{var} > P_{DA,t} \end{cases}$$

where:

P_{PCR}[€/MW]: price of PCR market
P_{DA}[€/MWh]: price of day ahead market
C_{var}: variable costs of a plant
CAP_{min}: minimal technical load
CAP_{PCR}: capacity offered to PCR market

To further explain the above equation, the price on the DA market $P_{DA,t}$ in a given hour is either higher or lower than the variable costs C_{var} of the plant. This means that every additional megawatt of electricity sold on the DA market generates revenues $P_{DA,t} - C_{var}$, or that the minimal technical load CAP_{min} required to operate a power plant to supply PCR, causes costs $C_{var} - P_{DA,t}$. Hence, the minimum PCR price should be higher than or equal to the sum of the two scenarios presented above. To acquire more accurate forecasts, it is important to consider the price of the PCR market of the previous week in the forecast model. Therefore, the forecast model weights the PCR prices of the previous week with a factor of two and PCR prices calculated by the above presented equation with a factor of one [34].

All costs related to actions needed to keep the storage system in operation throughout the duration of its economic life are considered fixed O&M costs. Variable O&M refer to the costs related to the operation of the storage system throughout the duration of its economic life with respect to the annual discharge energy and is expressed as cents/kWh. From literature review, variable O&M costs are around 0.3 cents/kWh-year [37].

The bidding strategy is also related to the profile of the bidder. In the table below are presented three types of bidders: the risk-averse bidder, the risk-neutral bidder and the risk-prone bidder. For each one the bidding strategy A, B and C respectively is presented. The weighted average PCR price (p_{wa}) of the bidding prices of all generation units is used as a basis for the risk-neutral strategy B. The risk-averse strategy A and the risk-prone strategy C are defined as p_{wa} ± 5 % respectively [34].

Table 4: Bidding strategies per bidder profile

Strategy	Corresponding value of forecast simulation
A	$p_{wa} \cdot 95\%$
B	p_{wa}
C	$p_{wa} \cdot 105\%$

Apart from participating in the Day-Ahead market, the investor has the option to participate in the Secondary Control Reserve (SCR) market for the provision of aFRR (automatic Frequency Restoration Reserve). However, according to an analysis presented in [20], the estimated FCR revenue is higher than the revenue potential on the aFRR market. Additionally, more researches presented in [38,39] suggest that capacity costs of BESS are too high to satisfy the 4-hour minimum operating criterion of aFRR. Moreover, large frequency deviations are very rare in the European grid, so the BESS performs small cycles when provisioning FCR in comparison to aFRR. Hence, deterioration costs are lower when providing FCR than aFRR [20]. Therefore, all the above mentioned attributes should be considered when comparing the two alternatives. However, in case of unsuccessful bids in PCR market, capacity can be provided in the SCR.

5.5 Price paths

The economic feasibility of the investment strongly depends on the PCR price development in the following years, as it affects the economic revenues. However, it is not clear yet how the increasing number of market participants and the entry of BESS will influence the PCR price and vice versa [34]. Therefore, four different price paths have been outlined to indicate the influence of the prices for the BESS plant. We assume that all four paths start in the year 2015 at a level of 3,500 €/MW per week. In the first scenario, a price jump from 3,500 €/MW to 2,500 €/MW per week is considered, corresponding to the average PCR capacity price of 2016. From 2016 on, the PCR capacity price is assumed to remain constant on this level. The second path models a decrease of PCR capacity prices from 3,500 €/MW to 1,000 €/MW per week, with a linear decrease with a slope of 500 € per year. The third price scenario, also models a decrease of PCR capacity prices from 3,500 €/MW to 1,000 €/MW per week, with an exponential decrease of the form shown below:

$$P_{PCR}(t) = P_{PCR,s} + \left(P_{PCR,0} - P_{PCR,s}\right) * e^{-\lambda t}$$

where t is the time in years, p the average PCR capacity price in the respective year, p_s the saturation price, p_0 the average PCR price in the base year, and λ the exponential decay constant. The last price path also assumes an exponential decrease of PCR prices as described by the previous equation but they differ regarding their saturation prices p_s and their decay constants λ. In the figure below the four paths described above are presented [34]. In general, from 2035 we expect a stabilization of PCR prices as the market will be more mature. The price paths presented below will be used for the estimation of the revenues and the economic feasibility of the investment.

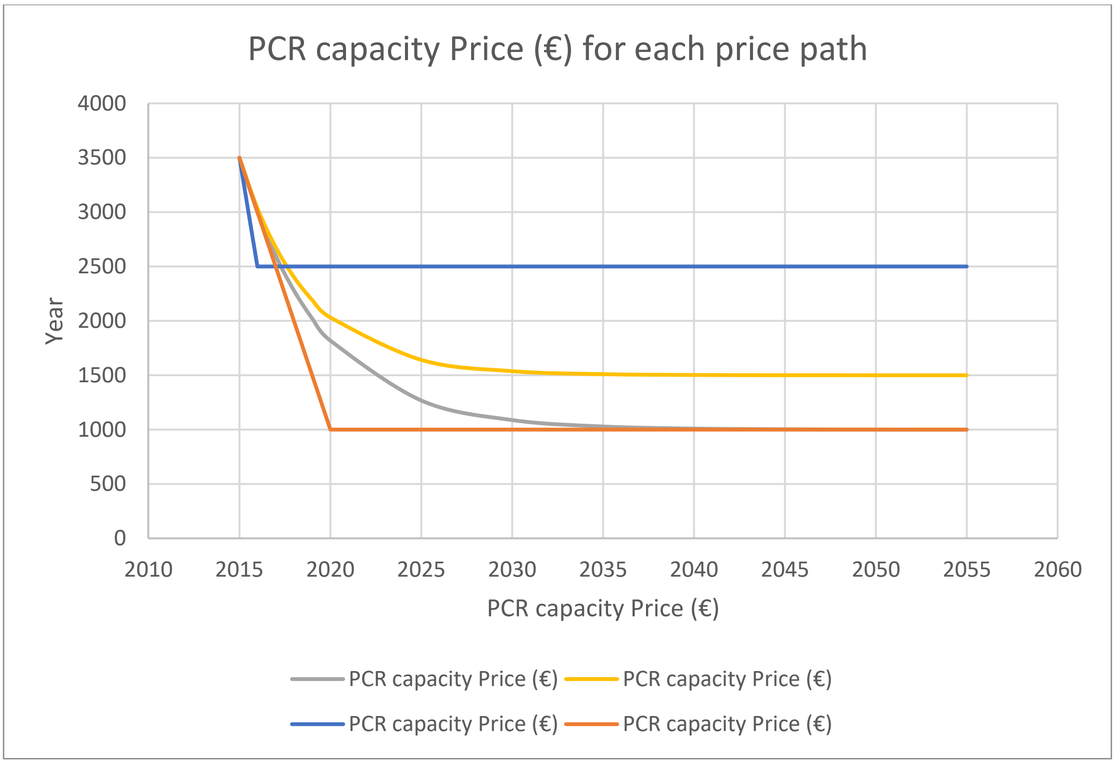


Figure 14: PCR capacity Price (€) for each price path

6. Results

6.1 Investment Assessment

In order to investigate how the revenues, and hence the economic feasibility of BESS, are influenced by the market development, we focus on the effect of two main factors: the impact of the long-term development of the PCR market for each price path and the impact of availability of the plant. In the following sections, the impact of each of the above mentioned factors on the net present value (NPV) and the internal rate of return (IRR) of the investment will be presented.

6.2 Impact of PCR price development on revenues

The investment for the BESS depends on the year of system commissioning since battery system prices are currently decreasing fast. In the graphs below are shown the average daily PCR prices from years 2017-2021. As it shown, there is a significant drop in prices, which is related to reduced expected revenues. It is mentioned that before July 2019, FCR was auctioned in weekly blocks with a service compensation based on the individually submitted capacity price (pay-as-bid). From July 1st, 2019, each day is auctioned independently and a uniform capacity price is paid to all successful participants. Moreover, before May 2019, each FCR prequalified unit was required to provide the auctioned power for 30-minutes in both fulfilment directions. Following new regulations coming into place at start of May 2019, the minimum delivery duration was reduced to 15-minutes [20].

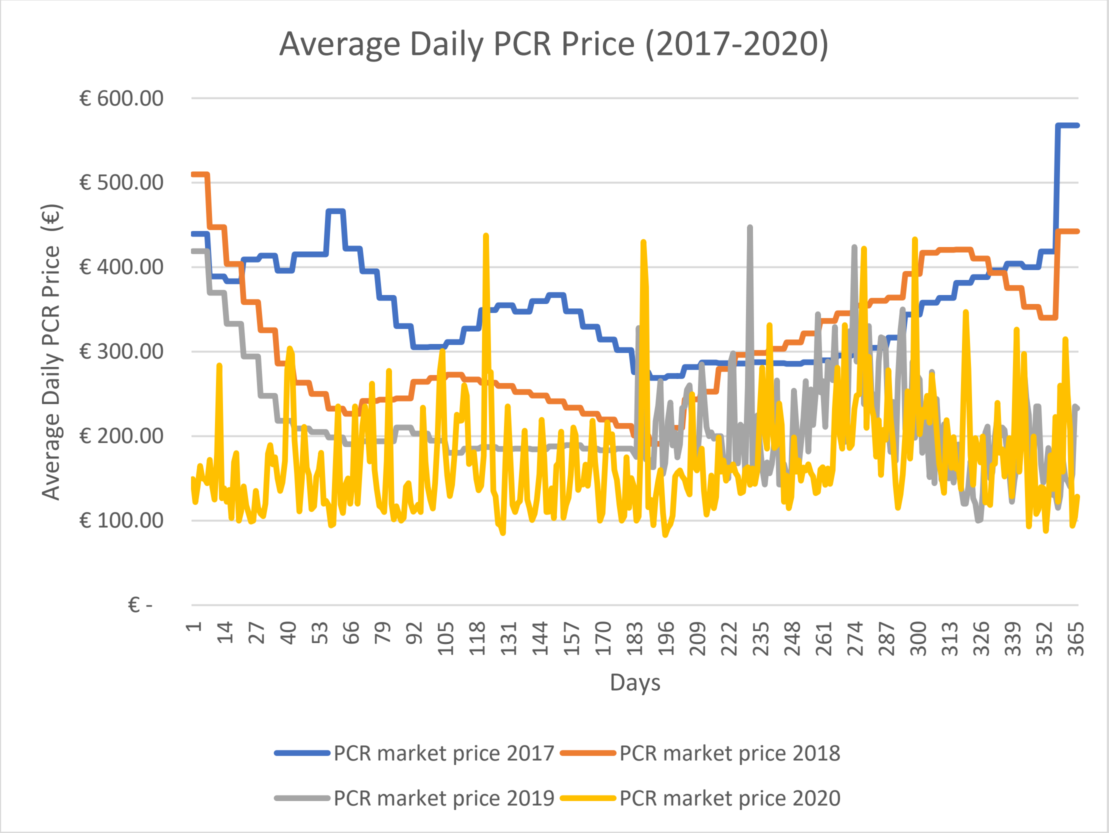


Figure 15: Average daily PCR price 2017-2020

From the above, we understand the importance of price stability and price forecasting in the revenues of the investor. In the graph below, we compare the annual revenues of 2017, 2018, 2019 and 2020, assuming 100% availability of the site, in order to further highlight the impact of the drop of prices.

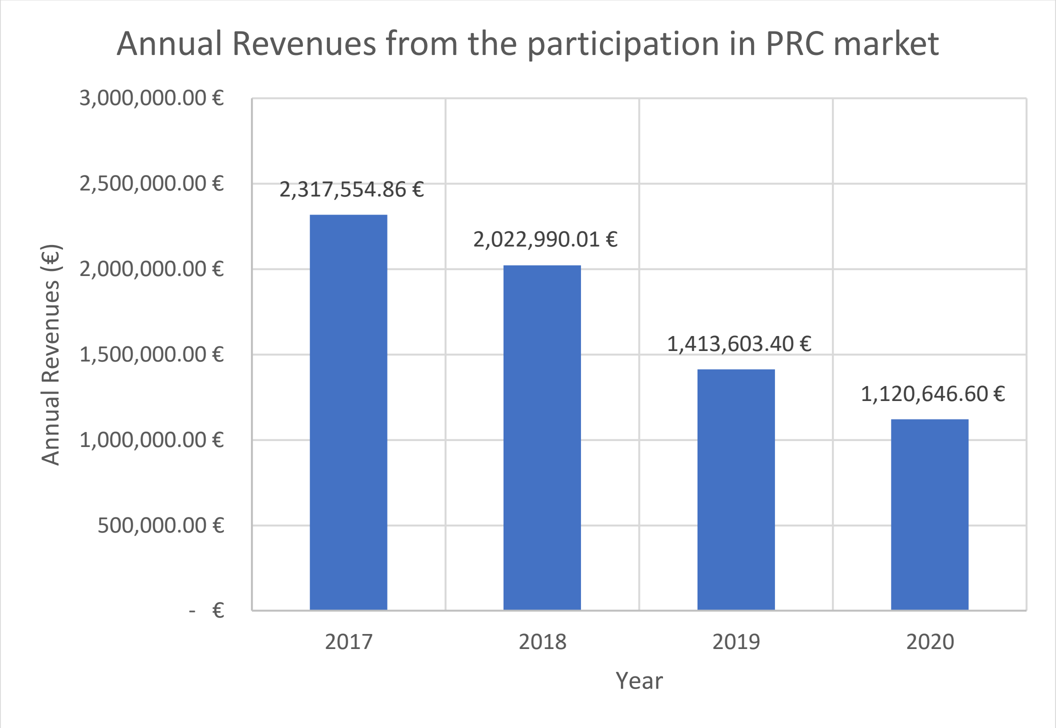


Figure 16: Annual Revenues from the participation in PCR market

6.3 Impact of availability on revenues

In order to assess the economic feasibility of the distinct operation strategies, we present below a realistic operation of the BESS in 2020, with days of full, partial and no participation in the PCR market, with an annual average availability of 93%. It is highlighted that the renumeration is done by the available capacity and not by the actual requested MW for PCR power.

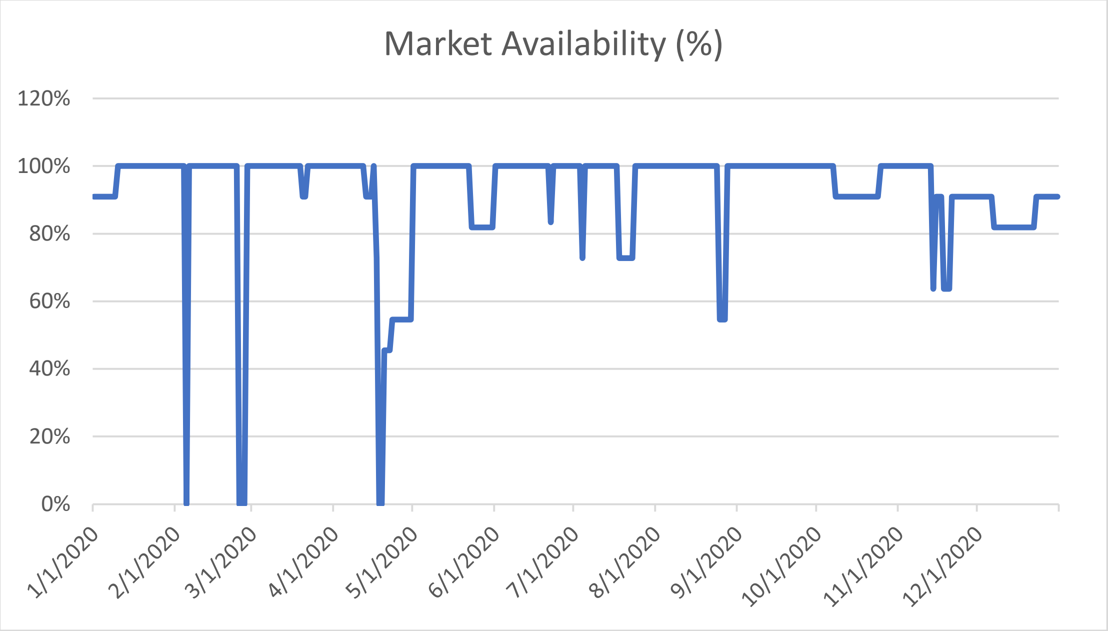


Figure 17: Market availability (% of 22MW)

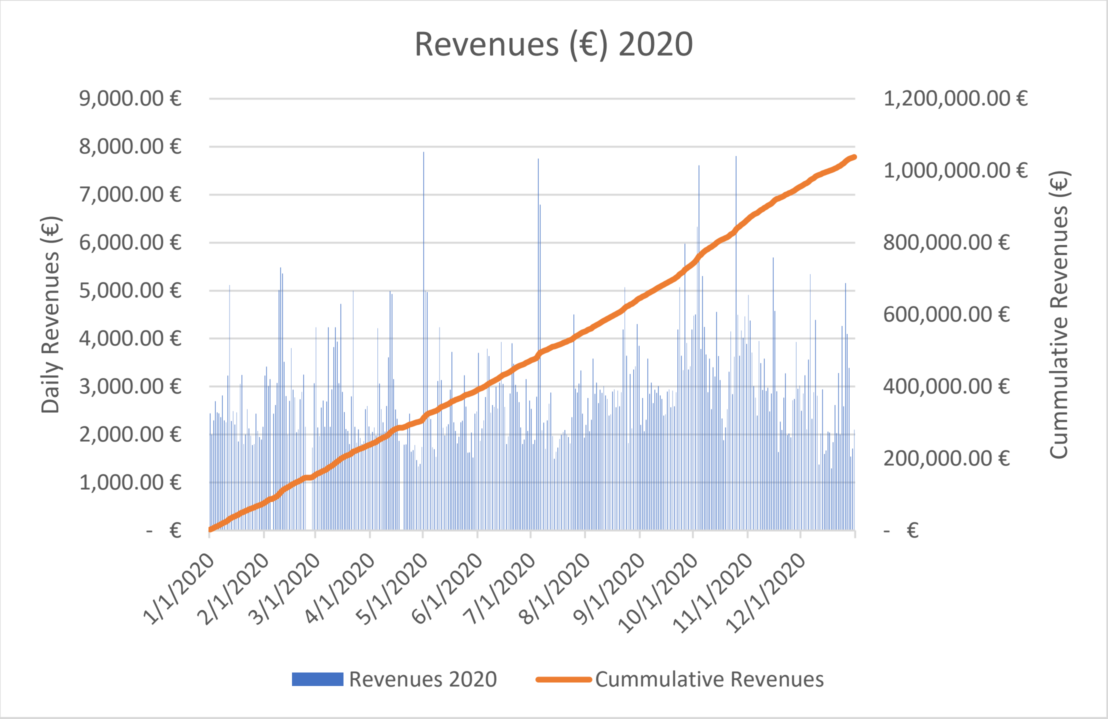


Figure 18: Daily and cumulative revenues in 2020 considering the availability of Figure 17

In the graph below, a comparison between the expected revenues (100% availability) and the actual revenues (93% availability) from the participation in the PCR market is presented. It is shown that in years with higher daily prices, the impact of availability is more critical, than in years with lower prices.

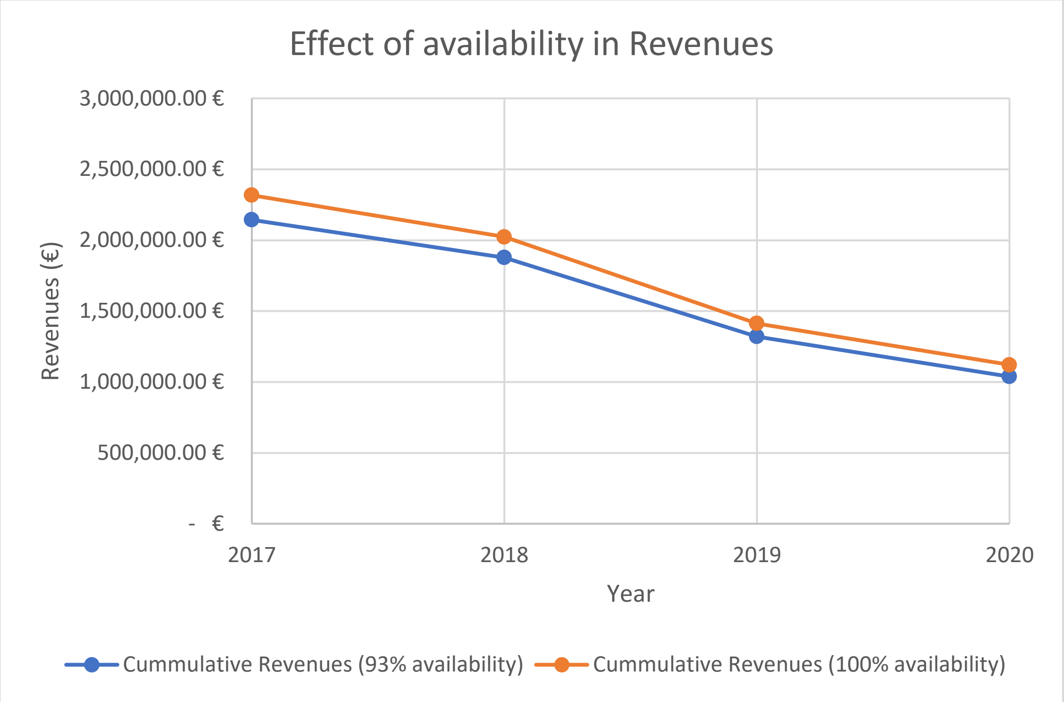


Figure 19: Effect of availability in Revenues from the participation in PCR market

6.4 Impact on NPV and IRR

Considering the above analysis, for the economic assessment of a battery storage system investment, the NPV and the IRR will be presented for a system with a lifetime of 20 years. We will examine the scenarios of the four price paths for availability cases of 100% and 93%. In the table below the main assumptions for our calculations is presented.

Table 5: Input data used for the economic assessment of the BESS

Total Investment Cost (€)	12,000,000.00 €
Loan Share	80%
Loan interest (%)	2.5%
Loan duration (years)	15
Trading cost (% of PCR revenues)	18%
Total Replacement expenses (€)	1,795,000.00 €
O&M expenses (€/year)	25,000.00 €
Insurance expenses (€/year)	68,000.00 €
Tax (%)	25.0%
Depreciation (%)	5.5%
Discount rate (%)	7.5%
Weighted Average Cost of Capital - WACC (%)	3.00%
Lifetime of the plant (years)	20

In the following tables, the net present value, the internal rate of return and the years of depreciation of the investment for the above mentioned scenarios are presented.

Table 6: NPV, IRR and years of depreciation considering 100% availability

Availability 100%				
	PCR_Scenario_1 (€)	**PCR_Scenario_2 (€)**	**PCR_Scenario_3 (€)**	**PCR_Scenario_4 (€)**
NPV	16,120,956.14 €	4,486,496.77 €	7,279,310.81 €	10,285,607.42 €
IRR	15%	8%	11%	13%
Years of depreciation	6	11	7	6

Table 7: NPV, IRR and years of depreciation considering 93% availability

Availability 93%				
	PCR_Scenario_1 (€)	**PCR_Scenario_2 (€)**	**PCR_Scenario_3 (€)**	**PCR_Scenario_4 (€)**
NPV	14,243,259.74 €	3,320,780.99 €	5,995,543.58 €	8,791,609.66 €
IRR	14%	7%	10%	12%
Years of depreciation	7	12	8	7

The graphs for the most probable scenario (availability 93% and PCR scenario 3) are shown below:

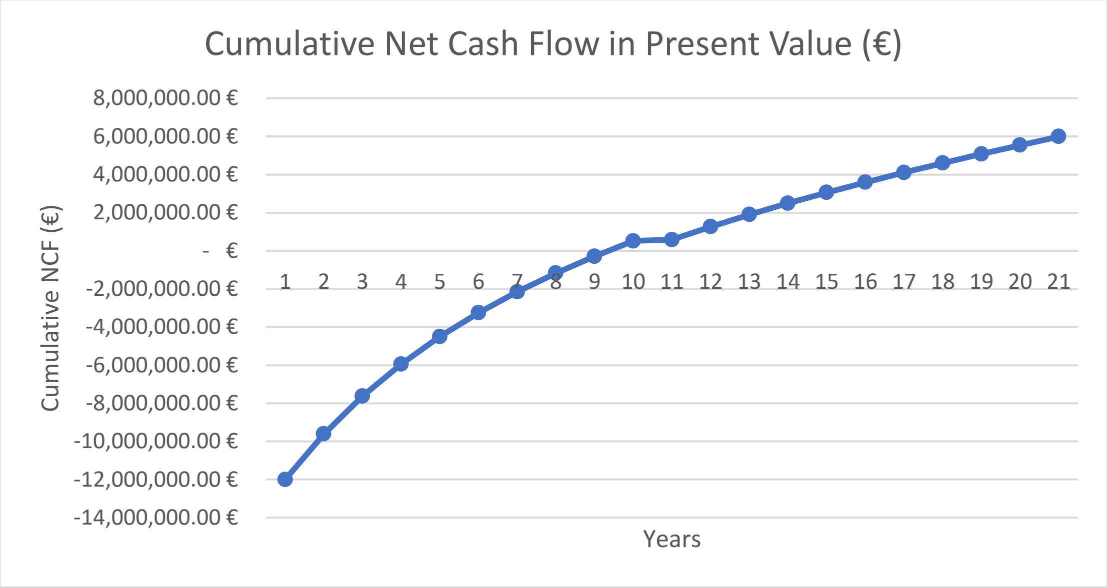


Figure 20: Cumulative NFC in Present Value for the most probable scenario

From the tables above, it is shown that the effect of both availability and prices are crucial factors for the assessment of the investment. Of course, the higher the prices and the availability, the better the results are. However, even in the worst case scenario (availability 93% and PCR scenario 2) the investment is worthy for a lifetime of 20 years. On the other hand, the lower the prices and the availability, the greater the risks are, as the years of depreciation of the investment will increase and the values of NPV and IRR will be lower. It is worth mentioning that 20 years is a pessimistic approach, as usually such investments are examined for a horizon of 25-30 years. However, as we are in a volatile market, we choose to examine the investment for less years.

7. Conclusion

Battery Energy Storage technologies have an active role in today's power networks and play a major role in the provision of ancillary services, as their fast response and reliability can guarantee the stability of the power systems.

Balancing market services in Europe are in a development phase, with regulatory framework and price volatilities. Germany is one of the countries with the higher installed capacity of energy storage systems with the majority of them participating in the FCR provision.

In this thesis, we focused on the operation of a battery energy storage system in the German area and its participation in the PCR market. In general, an investment in a BESS should be assessed considering its technical characteristics (such as SoC prerequisites, aging model, etc.), the volatilities in PCR prices and the impact of the availability of the plant, as these are strongly related to the expected revenues. Hence, different strategies available in order to mitigate losses, such as participation in other markets, penalties for technical unavailability, decommissioning option and use of batteries in other applications after their replacement should also be examined.

8. Future work

In future work, we could examine also the impact of different bidding strategies on the economic feasibility of the investment of a BESS, such as the participation in the Day-Ahead market or/and the participation in the Secondary Control Reserve market. The combination of the participation in different markets may increase the revenues, however the effect on the operation should be considered, specifically in relation to the charging and discharging limitations of the BESS.

Another issue that could be considered refers to the availability of the BESS. In many Operation & Maintenance contracts, a penalty regarding the technical availability of the system is considered in order to mitigate losses and thus highlighting the effect of availability on the revenues of the system.

Moreover, regarding the aging of the Lithium-Ion batteries, their exploitation in other applications after they reach a State-of-Health less than 80% should be examined. Following the same principle, a decommissioning option should also be considered, when the investment seems to be uneconomical. Hence, revenues from such actions can also be considered in the analysis of the economic feasibility.

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