

Competitiveness of Battery Energy Storage in the Future Belgian Capacity Market

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Executive Summary

As the world is transitioning from conventional to renewable energy sources, governments and energy utilities face the challenge to match the supply profile of these intermittent sources to the energy demand. Energy storage is being considered as one of the potential solutions to cope with the variability of renewables.

Belgium is not only challenged by the transition to renewable energy but must also deal with the total nuclear power phase-out by 2025. The country significantly depends on the seven nuclear power plants since they account for more than half of the national electricity production (depending on the availability of the reactors). The Belgian TSO *Elia* has investigated the urgency of adequacy and flexible electricity sources and proposed a Capacity Remuneration Mechanism (CRM), which should encourage investments in generation capacity to maintain the security of supply in Belgium. All awarded capacity providers of the competitive auction receive financial compensation for the availability of their generation capacity in the Belgian energy market.

Eneco is one of the largest utility companies in the Belgian electricity market for consumers and provides clean energy through their wind and solar farms. However, Eneco has no flexible generation capacity in Belgium, which makes the company more sensitive to high electricity prices because of the abundant supply of solar and wind energy. Electrical Energy Storage (EES) can reduce the risk of financial losses during high electricity prices and can be seen as an additional income-generating asset next to Eneco's existing wind and solar assets in Belgium. Therefore, Eneco considers participating in the Belgian capacity auction with EES capacity. As a result, this leads to the following main research question:

What is the competitiveness of electrical energy storage in the future Belgian capacity market?

The competitiveness of EES is assessed based on the constructed competitiveness evaluation model. The model considers the long-term capacity remuneration, possible costs related to the capacity market, storage costs, and revenue derived in the electricity market. A capacity provider is considered as competitive if the expected costs are smaller than the expected revenue from being in the capacity market. The net present value (NPV) approach is chosen to investigate the economic competitiveness of EES. The storage costs, intraday market income, payback obligation, and FCR income are modelled for the photo years 2020, 2025 and 2030.

The most suitable storage technology for participating in the Belgian CRM auction, and considered in this research, is Li-ion Battery Energy Storage (BES). This technology has favourable characteristics such as short response time, high power and energy density, high round-trip efficiency and low costs. Competing storage technologies are Large-scale Pumped Hydroelectric Energy Storage (PHES) and Compressed Air Energy Storage (CAES), however, both are not suitable in Belgium due to geographical restrictions.

The Battery Energy Storage System (BESS) will be deployed in the Frequency Containment Reserve (FCR) market and intraday market because of the largest revenue potential. FCR price is not expected to rise in the future and more likely to fall because of the increase of flexible generation capacity and the further integration of European ancillary service markets. Three FCR price scenarios are taken into consideration for calculating the FCR income. The FCR price will be equal to today's average FCR price (€ 79.000/MW/year), the FCR price will be equal to the minimum FCR price scenario observed since July 2019 (€ 51.000/MW/year) and the FCR price will be equal to the halved today's average FCR price (€ 39.000/MW/year). The expected intraday market income is assessed by the software tool Linny-R which applies the optimization technique linear programming based on the rolling horizon approach. The expected intraday market income varies from € 16.000/MW/year in 2021 to € 19.000/MW/year from 2030.

BESS operating only in the intraday market is not expected to be competitive because of the relatively high required capacity remuneration above € 100/kW/year. Auction clearing prices in other European CRMs are below € 50/kW/year.

BES does not need capacity remuneration from 2025 onwards with today's average FCR price. However, it is not very likely that the FCR price stays the same in the future, as described above. More realistic is 35% capacity price reduction from the average FCR price scenario of € 79.000/MW/year to the minimum FCR price scenario of € 51.000 /MW/year. BES might be competitive in this scenario with a relatively high de-rating factor and no payback obligation of the CRM. In the halved today's average FCR price scenario, BES will not be competitive in 2025 given the relatively high required capacity remuneration of minimum capacity remuneration of at least € 69/kW/year. BES might be competitive in 2030 with the halved today's average FCR price since the required capacity remuneration is at least € 21/kW/year. However, the capacity market might be already saturated with capacity providers bidding near zero in the auctions. Decisive parameters for competitiveness are the reference price, strike price and the de-rating factor.

The results of this research are not convincing to regard BES as a competitive technology in the upcoming Belgium capacity market. Revenue stacking by combining the FCR and intraday market income would increase the competitiveness of BES and is necessary. Further research should focus on deployment strategies of BESS in different markets and FCR price developments.

Contents

Acknowledgements	3
Executive Summary	4
Contents	7
List of Figures	11
List of Tables	13
1. Introduction	15
1.1 Problem statement	15
1.2 Research objective	17
1.3 Outline	18
2. Literature review	19
2.1 Capacity Remuneration Mechanism	19
2.2 Central buyer mechanism based on reliability options	22
2.2.1 Reliability options mechanisms in Europe	22
2.3 Electrical Energy Storage (EES)	23
2.3.1 Presence of EES on European capacity markets	24
2.4 Competitiveness	26
2.5 Knowledge gap	27
3. Research questions and approach	30
3.1 Research questions	30
3.2 Research approach	31
3.3 Methods	33
3.3.1 Net Present Value	33
3.3.2 Linny-R	34
4. System description	36
4.1 Characteristics of the Belgian CRM	36
4.1.1 Description	37
4.1.1.1 Market reference price and strike price	38
4.1.1.2 Availability requirements and availability penalties	41
4.1.1.3 Clearing algorithm	42
4.1.1.4 Demand curve and price caps	43
4.1.1.5 T-1 reserved volume	43

4.1.1.6 Minimum participation threshold	43
4.1.1.7 De-rating factors	44
4.1.1.8 Investment levels	46
4.1.2 Conclusions	47
4.2 Appropriate EES technologies	48
4.2.1. Common BES projects	50
4.3 Opportunities in the electricity markets	51
4.3.1 Wholesale electricity market	51
4.3.1.1 Description	51
4.3.1.2 Analysis	53
4.3.2 Ancillary services	54
4.3.2.1 Description	54
4.3.2.1.1 Frequency Containment Reserve	56
4.3.2.1.2 Automatic Frequency Restoration Reserve	57
4.3.2.1.3 Manual Frequency Restoration Reserves	57
4.3.2.2 Analysis	58
4.4 Price developments	61
4.4.1 Intraday market	61
4.4.1.1 Relation between day-ahead and intraday market price	62
4.4.2 FCR	64
5. Model description	65
5.1 Conceptual model	65
5.2 BESS setup	66
5.2.1 Dimensioning	66
5.2.1.1 Intraday market	66
5.2.1.2 FCR market	67
5.2.1 Costs and technical parameters	68
5.3 Intraday market income modelling	69
5.3.1 Description	69
5.3.1.1 Roll and look-ahead period	70
5.4 FCR income modelling	71
5.4.1 Charging costs	73
5.5 CRM contract length	74

5.6 Scenarios	77
5.6.1 CRM design scenarios	77
5.6.2 Intraday market price scenarios	78
5.6.2.1 Payback obligation	79
5.6.3 FCR price scenarios	80
5.7 Experiment design	81
6 Verification and validation	83
6.1 Verification	83
6.2 Input validation	85
6.3 Model validation	86
7. Results	87
7.2 Competitiveness in the intraday market	88
7.2.1 Doubling the depth of storage	89
7.2.2 Conclusions	90
7.3 Competitiveness in the FCR market	91
7.3.1 Average FCR price scenario	91
7.3.2 Minimum FCR price scenario	92
7.3.3 50% Average FCR price scenario	93
7.3.4 Revenue stacking of FCR and intraday market income	94
7.4 Conclusions	95
8 Discussion	96
8.1 Results	96
8.1.1 Intraday market income	96
8.1.2 Payback obligation	97
8.1.3 FCR income	98
8.2 Limitations	99
8.2.1 Data	99
8.2.2 Method	99
8.2.2.1 Net Present Value	99
8.2.2.2 Linny-R	100
8.2.3 Model and analysis	100
8.3 De-rating factor methodology	101
8.3.1 Belgian methodology	101

8.3.2 BES operation strategies	103
8.3.3 UK methodology	105
8.3.4 Conclusions	106
9 Conclusions	107
9.1 Answers to the sub-questions	107
9.2 Answer to the main research question	110
9.3 Policy recommendations	111
9.4 Recommendations for further research	112
10 Reflection	113
10.1 Scientific relevance	113
10.2 Societal relevance	114
10.3 Link to the EPA programme	114
11 References	115
12. Appendices	133
12.1 Full cycle definition	133
12.2 Intraday market	134
12.2.1 Input prices	134
12.2.2 Income build year 2020	135
12.2.3 Income build year 2025	135
12.2.4 Income build year 2030	136
12.3 FCR market	137
12.3.1 Cycles and energy delivery on FCR market	137
12.3.2 Price scenarios	140

List of Figures

Figure 1. Price duration curve of the EPEX SPOT day-ahead market price 2013-2018 (Elyxis, 2019).....	19
Figure 2. Taxonomy of the capacity mechanism models (European Commission, 2015).	21
Figure 3. Rolling horizon approach (Lu, Ying, & Chen, 2016).	35
Figure 4. Belgian CRM timeline until the first capacity auction (Elia, 2019i).....	36
Figure 5. Application of reliability options (Vázquez, Rivier, & Pérez-Arriaga, 2002).	38
Figure 6. Price development of Li-ion battery pack price outlook till 2030 (BloombergNEF, 2019a).	49
Figure 7. Sorted (high-low) difference in Belgian intraday and day-ahead prices of consecutive hours for a half year between December 4, 2018, and June 4, 2019. (Eneco, personal information, June 26, 2019).	53
Figure 8. Sorted (high-low) difference in Belgian intraday and day-ahead prices of consecutive hours for a half year between December 4, 2018, and June 4, 2019, < 100 hours. (Eneco, personal information, June 26, 2019).	53
Figure 9. Average day-ahead market price forecasts in Belgium 2020-2030 under different CO ₂ and technologies.	62
Figure 10. Hourly VWAP Belgium intraday and day-ahead market prices March 2019..	62
Figure 11. Hourly VWAP Belgium intraday and day-ahead market prices (per month) January 2014 - July 2019.....	63
Figure 12. Competitiveness evaluation model.	65
Figure 15. Linny-R model for calculating the intraday market income.	69
Figure 17. Marginal capacity price in Belgium on the regional platform between July 1, 2019 – September 29, 2019 (Regelleistung, n.d. -b).	71
Figure 18. Continental Europe synchronous area frequency 3-3-2018 00:00 - 4-3-2018 0:00 (RTE, 2019).	72
Figure 19. Intraday market income (2026) by operating different number of cycles.	75
Figure 20. Aggregated intraday market income for different BES lifetime (years).	76
Figure 16. Payback obligation in 2025 with strike price € 125/MWh.....	79
Figure 21. Verification of Linny-R model of 2026.	83
Figure 22. Required capacity remuneration, given the day-ahead market income in the reference scenario and in the optimistic scenario (2020, 2025, 2030).....	88
Figure 23. Breakdown of the EBIDTA for 2020, 2025 and 2030.....	90
Figure 24. Required capacity remuneration, given the average FCR price in the reference and optimistic scenario (2020, 2025, 2030).	91
Figure 25. Required capacity remuneration, given the minimum FCR price in the reference and optimistic scenario (2020, 2025, 2030).....	92
Figure 26. Required capacity remuneration given 50% of the average FCR price in the reference and optimistic scenario (2020, 2025, 2030).....	93
Figure 27. Combining intraday market and FCR incomes.	94

Figure 28. Process overview of the methodology for determining the de-rating factors of the Belgian CRM (based on Elia, 2019e).	101
Figure 29. Alternative contributions of BES to shortage periods (Based on Dent, Wilson Zachary, 2017).	104
Figure 14. Cycling process (Thirugnanam, Saini., & Kumar, 2012).....	133

List of Tables

Table 1. Auction results of battery storage in Irish all-island and United Kingdom (EirGrid., & SONI, 2018; EirGrid., & SONI, 2019a; EirGrid., & SONI, 2019b; National Grid, 2018a; National Grid, 2018b; National Grid, 2019).....	24
Table 2. Current state of scientific knowledge on the relevant subjects for evaluating the competitiveness of EES in the future Belgian capacity market.....	29
Table 3. Set of BESS constraints and description (Hu., Chen., & Bak-Jensen, 2010).....	34
Table 4. Elements determining the functioning of the CRM (Elia, 2019i).	37
Table 5. Possible outcomes reliability options (Vázquez, Rivier, & Pérez-Arriaga, 2002).	39
Table 6: Mentioned strike prices in Italy and Irish all-island CRM (European Commission, 2018; EirGrid, & SONI, 2019).	40
Table 7. SLA categories for energy-constrained capacity providers. Adapted from Elia (2019k).	41
Table 8. United Kingdom and Irish all-island De-rating factors T-4 capacity auction (deliver year 2022/23) and Poland de-rating factors capacity auction (delivery year 2021-2022, 2022-2023, 2023-2024) (Rozporządzenie Ministra Energii; 2018; EirGrid., & SONI, 2019; National Grid, 2018c).	45
Table 9. Investment levels of European CRMs (CREG, 2019).	46
Table 10. Specification of the three EPEX SPOT Belgium market segments (EPEX SPOT, n.d. -e).....	52
Table 11. Overview of the (future) ancillary services (Elia, 2017a; Elia 2018d; Elia, 2019b).....	55
Table 12. Technical characteristics ancillary services (Elia, 2017a; Elia, 2018a; Elia, 2019b; Elia, 2019c).	58
Table 13. Average price of selected bids for the ancillary services between January 2019 – week 31 August 2019 (Elia, n.d. -c).	60
Table 14. BESS setups taken initially into consideration.	67
Table 15. Li-ion BESS costs parameters and values (IRENA, 2017; Eneco, personal information, May 21, 2019; Eneco, personal information, August 2, 2019; XE, 2019; Statbel, 2019; KBC, 2018).....	68
Table 16. Investment levels of European CRMs (CREG, 2019).	74
Table 17. Reference scenario and experiments for calculating the required capacity remuneration.....	77
Table 18. Average day-ahead market price 2018 predictions for 2020, 2023, 2025, 2028, 2030 including percentage change.	78
Table 19. Payback obligation with strike price € 125/MWh (2021-2030).....	79
Table 20. Year description of scenarios 2020, 2025 and 2030.....	81
Table 21. Experiments for BESS (10 MW/10 MWh) operating in the intraday market..	81
Table 22. Experiments for BESS (12,5 MW/10 MWh) operating in the FCR market.	82

Table 23. Experiments for BESS (12,5 MW/10 MWh) operating in both the intraday and FCR market.....	82
Table 24. Published (approximated) project costs by developers compared to IRENA's estimated storage costs (Infigen, 2018; Enel, 2019; Endesa, 2017; IRENA, 2017).....	85
Table 25. Income differences in the intraday market and the FCR market (2020, 2025, 2030).....	95
Table 26. Deals on the EPEX intraday market 1-1-2018 02:00.	96
Table 27. Influence of the payback obligation on the required capacity remuneration. .	97

1. Introduction

1.1 Problem statement

The worldwide energy consumption should drastically change the coming decennia to avoid dangerous climate change. In 2015, 175 parties signed the Paris Agreement to keep the global temperature rise this century below 2 degrees Celsius, aiming for 1,5 degrees Celsius (UNFCCC, 2015). In the same year, all the United Nations Member States adopted the Sustainable Development Goals to provide affordable and clean energy for everyone by 2030 (United Nations, 2015). Every country in the world faces the major challenge of reducing greenhouse gas emissions.

Renewable energy sources, such as wind and solar energy, offer great opportunities to make the energy supply more sustainable. However, the energy production of these sources strongly depends on weather conditions. Besides, the energy consumption varies per part of the day but also per season. The difference between the supply profile and the energy demand is considered as a major challenge for governments, utility companies, and transmission system operators (TSOs). Energy storage is considered as one of the major components of the solution to deal with the variable nature of wind and solar energy. By way of illustration, the world demand for battery storage is estimated to reach 2800 gigawatt-hours (GWh) in 2040 – corresponding to storing around half of 2019's global renewable energy production in a day (World Bank, 2019).

The transition to a low-carbon society with higher penetration levels of variable renewables is not the only challenge for Belgium. On January 31, 2003, the Belgian parliament approved the bill for the nuclear power phase-out, implying shutting down all seven nuclear power plants. No new nuclear power plants will be built for industrial electricity production (Belgisch Staatsblad, 2003). In the end, no electricity is generated from nuclear energy in 2025. Belgium significantly depends on nuclear energy, as nuclear power plants produce more than half of Belgium's total electricity production in 2017. Nuclear represented 34% of Belgium's electricity production in 2018 because of unavailability of nuclear multiple power plants, which led to a greater import of electricity from abroad (Elia, 2019a).

The Belgian minister of Energy has commissioned the Belgian TSO *Elia* to investigate the urgency of adequacy and flexible electricity sources to ensure the security of supply in the period 2017-2027. Elia cannot guarantee that the current energy-only market, combined with a strategic reserve mechanism, can ensure sufficient investments in generation capacity to maintain the security of supply in Belgium (Elia, 2016a). The proposed measure is a Capacity Remuneration Mechanism (CRM) based on reliability options and should succeed the strategic reserve mechanism (Belgische Kamer van volksvertegenwoordigers, 2019a).

The objective of the prospective Belgian CRM is to ensure a certain level of security of supply at the lowest possible cost. Capacity providers are remunerated in auctions for the availability of their capacity per megawatt (MW) in the energy market (Belgische Kamer van volksvertegenwoordigers, 2019a). On April 4, 2019, the Belgian federal parliament approved the bill for the adaption of the Belgian electricity act that allows the introduction of a CRM to encourage investments in capacity (Belgische Kamer van volksvertegenwoordigers, 2019a). According to Elia's recent adequacy and flexibility study, the new capacity required is 3,9 GW from 2025 to guarantee the security of supply after a full nuclear power phase-out. The assumption takes into account the limited options during the winter months because of planned coal exits of neighbouring countries and in particular Germany (Elia, 2019d). There will be one auction four years ahead of each delivery year and one auction a year ahead of each delivery year securing the capacity required (Belgische Kamer van volksvertegenwoordigers, 2019a). The first auction should take place in October 2021 to ensure sufficient capacity from November 2025 (Elia, 2019d).

The capacity auctions do not exclude any form of capacity because of the technological neutrality requirement imposed by the European Commission. Each capacity provider who can contribute to the security of supply can participate in the auction. Possible candidates are power plants, demand response, storage, and renewable sources (Belgische Kamer van volksvertegenwoordigers, 2019b). In the light of the world's energy transition to a sustainable energy future is whether storage is competitive with (existing) conventional plants in the Belgian capacity auction.

1.2 Research objective

Eneco is one of the largest utility companies in the Belgian electricity market for consumers (VREG, 2019). In 2019, Eneco has a substantial generation capacity of on- and offshore wind energy and solar energy (resp. 436 MW, 178 MW, 78 MW) in Belgium but no flexible capacity (Eneco, n.d. –a, Eneco, n.d. –b, Eneco, n.d. –c). This implies Eneco is more sensitive to high electricity prices when the sun does not shine, and the wind does not blow (Eneco, personal communication, April 25, 2019). Electrical Energy Storage (EES) can reduce the risk of financial losses during high electricity prices and aligns Eneco's mission ('everyone's sustainable energy') better than conventional power plants (Eneco, 2019). Also, EES can be seen as an additional income-generating asset next to Eneco's existing wind and solar assets in Belgium. Therefore, Eneco considers participating in the Belgian capacity auction with EES capacity.

The research objective is to evaluate the competitiveness of EES installed by Eneco in the future Belgian capacity market. The long-term capacity remuneration, possible costs related to the capacity market, storage costs, and revenue derived in the electricity market are integrated into one analysis.

1.3 Outline

This research is structured as follows:

- Chapter 2 includes the literature review. The literature review explains the scientific problem regarding EES in the future Belgian capacity market. This section discusses the core concepts and the formulation of the academic knowledge gap;
- Chapter 3 involves the main research question, sub-questions and the research approach including the methods used;
- Chapter 4 entails the system description, discusses the characteristics of the Belgian CRM and explores appropriate EES technologies. Subsequently, the chapter discovers opportunities in the Belgian electricity market and discusses price developments in the electricity market;
- Chapter 5 includes the model description including the conceptual model, BESS dimensioning, intraday market and FCR income modelling and the scenarios;
- Chapter 6 discusses verification and validation;
- Chapter 7 presents the results including the required capacity remuneration;
- Chapter 8 discusses the results and the limitations of this research;
- Chapter 9 presents the conclusions, policy recommendations and recommendations for further research;
- Chapter 10 entails the reflection on the scientific relevance, societal relevance and the link to the EPA programme;
- Chapter 11 includes the references;
- Chapter 12 involves the appendices;

2. Literature review

The core concepts of the research will be discussed and defined in this chapter. Eventually, the knowledge gap in existing research will be addressed.

2.1 Capacity Remuneration Mechanism

The ideal situation would be to have an electricity market which ensures the security of supply for the lowest consumer prices. Generation capacity investments might lead to more competitive market results and maintain the reliability of the electrical grid. However, power generation companies have to deal with demand uncertainty and competition. Besides, investments are to a large extent sunk costs, and generators have to make the investment decision at the right time (Genc, 2012). The investment in generation capacity is profitable if the expected revenue during production hours are at least equal to the investment costs (Mulder, 2017). The revenue of peak generation assets significantly depends on the frequency, height, and duration of price spikes (De Vries, 2007). Figure 1 shows the price duration curve of the hourly day-ahead market price on the Belgian EPEX SPOT exchange between 2013-2018 (Elyxis, 2019).

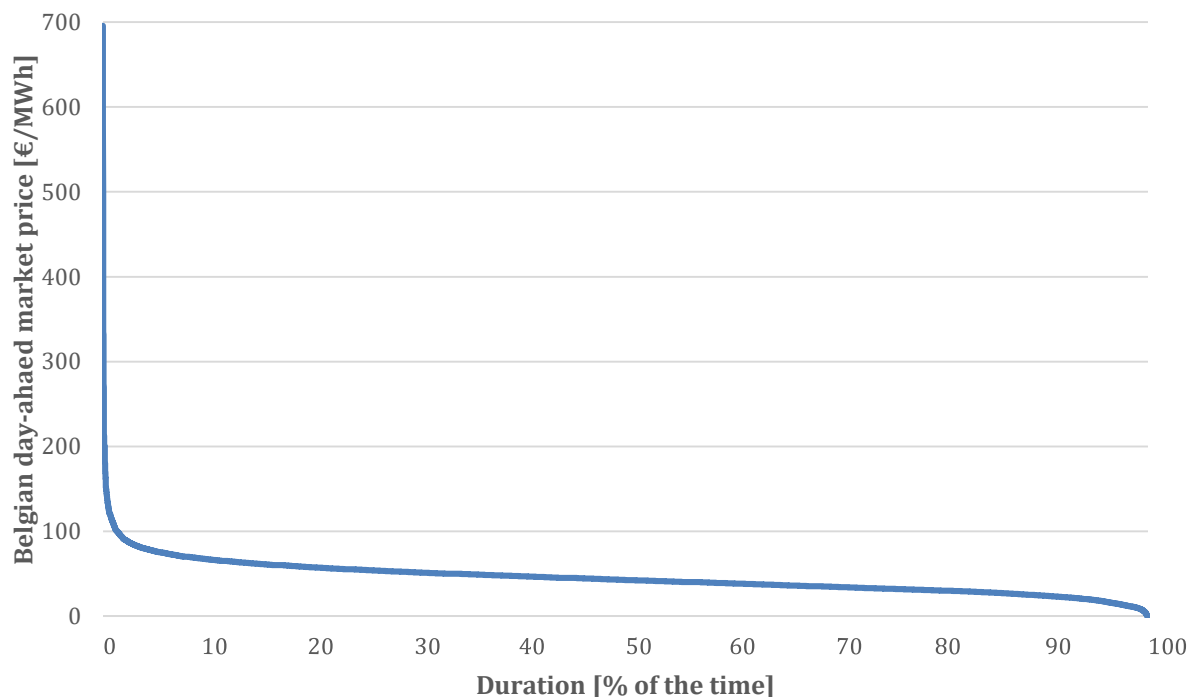


Figure 1. Price duration curve of the EPEX SPOT day-ahead market price 2013-2018 (Elyxis, 2019).

According to the underlying day-ahead market prices of the price duration curve, the price rises only about 3% of the time above 100 euros per megawatt-hour (MWh). Small differences in the occurrence of price spikes greatly affect the steepness of the price duration curve and thus the expected profitability of generation capacity investments (De Vries, 2007). Peak plants should recover their investment costs from these price spikes (Cepeda & Finon, 2011). However, peak prices are subject to the political debate because the introduction of price caps should protect consumers from prices higher than their value of lost load (de Vries, Correljé, & Knops, 2017). The situation where the revenue from the energy markets is insufficient for a generation asset to cover its capital and operating expenses is called the 'missing money' problem (Newbery, 2016).

If the market provides insufficient generation capacity to meet the demand without government intervention, the solution involves the introduction of additional mechanisms to ensure the security of supply (Batlle & Pérez-Arriaga, 2008). This situation applies to Belgium, where the energy-only market cannot provide proper investments incentives to ensure the security of supply after 2025 (Elia, 2019d). The European Directive 2003/54/EC has been implemented which provide designations for transmission and distribution system operators for direct interventions in the electricity market (Finon & Pignon, 2008). This development brings the introduction of capacity (remuneration) mechanisms (CRM) into the spotlight. The objective of all capacity mechanisms is to introduce incentives for utility companies to provide sufficient generation capacity, even in the situation of imperfect information or concerns regarding risk. Besides, it should stimulate to maximise utility companies' generation output during shortages in the electricity market (de Vries, Correljé, & Knops, 2017). Capacity mechanisms differ from one another in structure and implementation. All mechanisms each have their effects in the electricity market, and each country's implementation is unique (Meulman & Méray, 2012).

The capacity mechanisms can be divided into five types according to the European Commission (2015). The first classification is based on whether the mechanism is volume-based or price-based. Price-based means the TSO sets the price, and the volume depends on the willingness of investors. The opposite of price-based is volume-based where the TSO sets the volume, and market forces determine the price. Market-wide capacity mechanisms reward all forms of capacity, whereas targeted capacity mechanisms only reward a subset (Hancher, de Hauteclocque, & Sadowska, 2015). The volume-based capacity mechanisms can be divided into the following subgroups; targeted and market-wide. All five types of capacity mechanisms are presented in Figure 2. The type of capacity remuneration mechanism in the Belgian bill, and therefore relevant in this research, is the (market-wide) central buyer capacity mechanism based on reliability options, which is the red block in the figure below. The mechanism will be explained in 2.2.

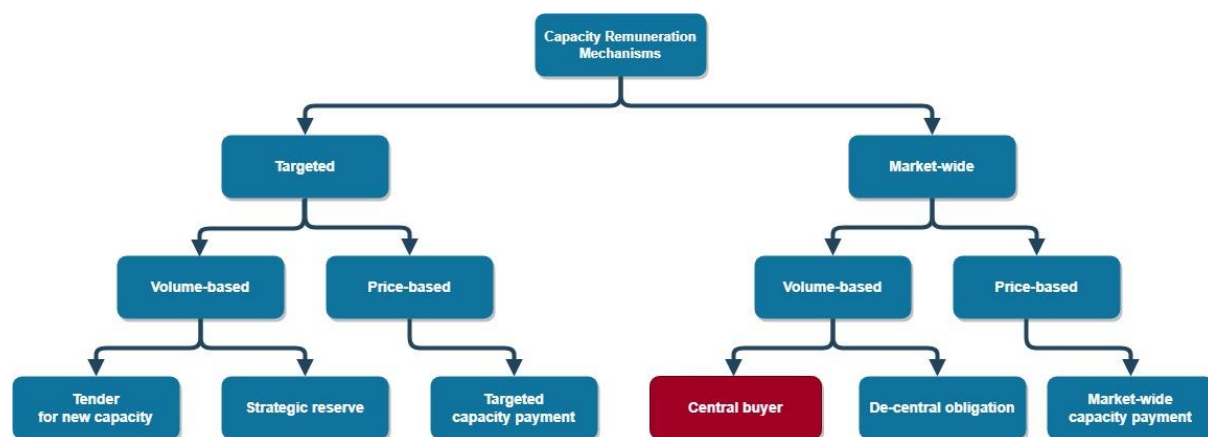


Figure 2. Taxonomy of the capacity mechanism models (European Commission, 2015).

2.2 Central buyer mechanism based on reliability options

Reliability contracts should provide capacity providers with better incentives for being active in the energy market during scarcity (De Vries, 2007). The central buyer mechanism based on reliability options has been first introduced by Pérez-Arriaga (1999) and further elaborated by Vázquez, Rivier, & Pérez-Arriaga (2002). It is often called in literature *reliability contracts*, *reliability options mechanism* and *energy call options auction* (Bidwell, 2005; Vázquez, Rivier, & Pérez-Arriaga, 2002; De Vries, 2007; Vázquez, Batlle, Rivier, & Pérez-Arriaga, 2003; Bezerra et al., 2006; Bezerra, Barroso, & Pereira, 2011).

The regulatory authority of the energy market, e.g., the TSO, prescribes the market to purchase reliability contracts, which represents the desired volume of capacity. The reliability contracts are procured in a competitive auction and are composed of a financial call option and a penalty for non-delivery of the auction item. The capacity providers receive a fixed remuneration for the awarded capacity in the auction. The call option of reliability contract entails that the contracted capacity provider should pay the positive difference between a reference price, e.g., electricity market price, and a predetermined strike price during the contracted period in return (often called the ‘payback obligation’). Capacity providers are penalized if they do not meet the delivery obligation. An elaborate explanation of the Belgian reliability options mechanism will be discussed in 4.1.

2.2.1 Reliability options mechanisms in Europe

Reliability options schemes have been approved by the European Commission in the United Kingdom (only Northern Ireland), Ireland and Italy in 2017 and 2018 (European Commission, n.d.). The electricity market on the island of Ireland, which refers to the Republic of Ireland and Northern Ireland, is managed and regulated collectively by the TSOs of the Republic of Ireland (‘EirGrid’) and Northern Ireland (‘SONI’) (European Commission, 2017a). The jointly CRM of Ireland and Northern Ireland¹ is hereafter referred to as Irish all-island CRM.

¹The Irish all-island electricity market operates as a single market under the same market wholesale electricity market arrangement *Integrated Single Electricity Market* (I-SEM) and capacity is reimbursed through one CRM.

2.3 Electrical Energy Storage (EES)

Electrical Energy Storage (EES) refers to the process of transforming electrical energy from the electricity distribution network into any form allowing temporary storage and transforming back to electrical energy when needed. The process makes it possible to store electricity during periods of low demand and supplying energy to the grid during periods of high demand or shortages (Chen, Cong, Yang, Tan, & Ding, 2009).

The characteristics of EES differ from conventional and non-conventional power plants, such as gas-fired generation assets and wind turbines. A major feature of EES is the short response time compared to non-conventional and conventional power plants. As an example, the response times of gas generation assets are between 4-45 minutes in hot starts (4-250 minutes in cold starts) and the response times of coal generation assets are between 100-300 minutes in hot starts (450-900 minutes in cold starts) (Gonzalez-Salazar, Kirsten, & Prchlik, 2018). In contrast, the response time of chemical storage, such as Li-ion batteries, is a few milliseconds (Evans, Strezov, & Evans, 2012). The short response time makes EES suitable for applications which require this feature, such as ancillary services.

EES technologies differ primarily in efficiency, response time, lifetime, energy and power capacity, and discharge time (Poullikkas, 2013). The storage characteristics of new installations improve over time as research on material science continues, and capital costs are coming down (Dvorkin et al., 2017).

The most common EES application in the world is (electric) energy time-shifting and accounts for 85% of the total EES applications (US DOE, 2017). Energy time-shifting involves buying and storing of (electric) energy when demand and energy prices are low and selling and releasing the energy when demand and energy prices are high (Energy Storage Association, n.d.-a). The objective is to find the most economically favourable buying and selling moments. Other applications are electric supply capacity (4%), black start (4%) and renewables capacity firming (3%) (US DOE, 2017).

2.3.1 Presence of EES on European capacity markets

Reliability options schemes are approved by the European Commission for the Irish all-island CRM and Italian CRM, as mentioned in 2.2.1. EES has not been successful in the Irish-island T-1 auctions (auction one year ahead the deliver year) in December 2017 and 2018, but has been successful in the T-4 auction (auction four years ahead the delivery year) in May 2019 (EirGrid., & SONI, 2018; EirGrid., & SONI, 2019a; EirGrid., & SONI, 2019b). The auction clearing price, the awarded de-rated battery capacity² in the CRM auction and the share of battery capacity of the total de-rated capacity for the Irish all-island capacity auctions are presented in Table 1. According to the Italian authority, the first capacity auction should take place before end of 2019, so there are no results yet (Terna 2019; Askanews, 2019).

CRM	Type	Date	Deliver year	Auction clearing price [€/kW/year]	Awarded de-rated battery capacity [MW]	Share of total de-rated capacity [%]
Irish all-island	T-4	May. 2019	2022/23	46,15	81	1,1
	T-1	Dec. 2018	2019/20	40,65	0	0
	T-1	Dec. 2018	2018/19	41,80	0	0
United Kingdom	T-1	Jun. 2019	2019/20	0,87 (£ 0,77)	23	0,6
	T-4	Feb. 2018	2021/22	9,52 (£ 8,40)	158	0,3
	T-1	Feb. 2018	2018/19	6,80 (£ 6,00)	113	1,9

Table 1. Auction results of battery storage in Irish all-island and United Kingdom (EirGrid., & SONI, 2018; EirGrid., & SONI, 2019a; EirGrid., & SONI, 2019b; National Grid, 2018a; National Grid, 2018b; National Grid, 2019).

² The de-rated capacity awarded in the CRM auction, which is the contributing to generation adequacy, is equal to the awarded nominal capacity times the relevant de-rating factor for the capacity provider (see 4.1.1.7).

The CRM in the United Kingdom differs from the upcoming Belgian CRM and existing Irish all-island and Italian CRM because it is not based on reliability options, which implies United Kingdom's CRM does not include the payback obligation for capacity providers. However, a lot of battery storage participate in United Kingdom's capacity auctions and therefore relevant to take into account. Battery storage projects have broken through in the United Kingdom and awarded since the T-4 capacity auction for 2021-2022 in December 2016 (National Grid, 2016). Full details of awarded battery capacity for T-1 auction on June 2019, T-4 auction and T-1 auction in February 2018 are presented in Table 1.

Remarkable is the significant difference in auction clearing price between the Irish all-island and United Kingdom's capacity auctions, and especially the latest T-1 auction in the United Kingdom with a clearing price near zero. This can be explained by the fact that T-1 auction is a 'top-up' auction of the main T-4 auction to meet the additional capacity demand of that particular deliver year. Therefore, less capacity is procured in the T-1 auction compared to the T-4 auction of the delivery year 2019-2020, respectively 3,7 GW versus 46 GW (National Grid, 2015; National Grid, 2019). The clearing price near zero can be explained by the large supply of (cheap) capacity. 9,4 GW entered the latest T-1 capacity auction, including 198 MW of battery storage, and only 38% was awarded. One new battery project and five existing battery projects are awarded, which in total accounted for only 0,6% of the total capacity. The big winners in this specific auction are, mostly existing, Combined Cycle Gas Turbine (CCGT), Open Cycle Gas Turbine (OCGT) and Combined Heat and Power (CHP) which accounts in total over 40% of the awarded capacity. The supply curve of the auction clearly shows a lot of capacity providers are willing to bid close to zero (National Grid, 2019). The example of the United Kingdom underlines the fierce competition in the capacity auction between technologies and new and existing assets.

2.4 Competitiveness

The conceptual term *competitiveness* has multiple meanings and depends upon context. Here, it is in the context of the economic feasibility of EES participating in the future central buyer mechanism based on reliability options in Belgium.

In theory, any capacity provider can be successful by bidding € 0/kW/year in the capacity auction, assuming that he meets all conditions of the CRM. However, an economically rational capacity provider would participate in the CRM if his expected costs are smaller than his expected revenue from being active in the capacity market. From the perspective of this research, the costs consist of the storage costs and possible costs arising from participating in the CRM, i.e., payback obligations and penalties. The expected revenue consists of the revenue derived in the electricity market and the capacity remuneration. Thus, the competitiveness of EES in the future Belgian capacity market can be expressed by the following inequality:

$$C_{storage} + C_{crm} < R_{market} + R_{crm}$$

As mentioned in 2.2, the missing money problem occurs if the revenue from the energy markets is insufficient for a generation unit to cover its capital expenses and operating expenses. Given the occurrence of the ‘missing money’ problem, the inequality above implies the capacity remuneration R_{crm} a capacity provider requires should be greater than the missing money (i.e., the revenue derived in the electricity market minus the storage costs $C_{storage}$ and the possible costs arising from participating in the mechanism C_{crm} .) Otherwise, there’s no economic incentive to participate in the market. This inequality is expressed by the equation below:

$$C_{storage} + C_{crm} - R_{market} < R_{crm}$$

The four cost and revenue components will be defined in the system description.

2.5 Knowledge gap

As mentioned in 2.2, much is known about capacity remuneration mechanisms in general and in particular the central buyer mechanism based on reliability options. However, no scientific research has been conducted on the performance of EES on a capacity market.

Over the past several years, a lot of research has been done on the role of utility-scale EES and identifying suitable technologies, given the increasing presence of Renewable Energy Sources (RES) (Ferreira, Garde, Fulli, Kling, & Lopes, 2013; Soloveichik, 2011; Dunn, Kamath & Tarascon, 2011; Ibrahim, Ilinca, & Perron, 2008; Divya, & Østergaard, 2009). The literature review showed that the most appropriate choice for an EES technology highly depends on the application. It is nearly impossible to give one simple, straightforward answer. Research has demonstrated that EES could contribute to the security of supply by, for example, lowering peak demand (Zhou, Mancarella, & Mutale, 2015). Methodologies have been introduced to quantify the contribution of an EES unit to the security of supply and estimate its capacity value, i.e., the quantification of the EES unit's effect on the system reliability (Zhou, Mancarella, & Mutale, 2015; Sioshansi, Madaeni, & Denholm, 2013; Konstantelos, & Strbac, 2018; Evans, Tindemans, & Angeli, 2019). However, scientific research lacks on the contribution of EES in capacity auctions and related market-specific rules.

The Belgian Commission for Electricity and Gas Regulation (CREG) and the Belgian federal government service *FOD Economy* carried out the most recent research of the possibilities of EES on specifically the Belgian electricity market in 2015 (CREG, 2015; FOD Economie, 2015). At that time, Pumped Hydroelectric Energy Storage (PHES) had the highest maturity in the study by FOD economy because of its high efficiency and high energy density, which makes it suitable for balancing energy supply and demand across the electric grid. Both studies explicitly mentioned that technology costs of storage could fall substantially in the coming years due to technological advances and economies of scale. Therefore, the results should be interpreted with caution because the findings are based on technology cost data from more than five years ago and are a poor indication of the economic feasibility of EES.

Two papers by Bezerra et al. (2006) and Bezerra, Barroso, & Pereira (2011) describe bidding strategies for capacity providers participating in Brazilian reliability options. The research focusses on calculating the optimal strike price bid, and option premium bid to maximise the capacity provider's revenue, given a desired risk-adjusted rate of return.

However, the described stochastic optimisation in the papers is less accurate for the European central buyer mechanism based on reliability options. First, the Brazilian reliability options mechanism differs from the European reliability options mechanism because both the premium fee and the strike price should be proposed by the capacity providers in the Brazilian auction. Second, the expected market revenue is calculated using Monte Carlo simulation for different hydrological scenarios (Bezerra, Barroso, & Pereira, 2011). The Brazilian power system is hydro-based, so the hydrological conditions influence the market reference price (Bezerra et al., 2006). However, they are less relevant in Europe since the European power system is not hydro-based. Besides, the calculation in the research for the expected premium fee per year assumes that a fraction of the hours per year the market reference price exceeds the strike price (Bezerra et al., 2006; Bezerra, Barroso, & Pereira, 2011). Estimates can be made more accurate by calculating the payback obligation based on market reference price forecasts.

Last, the variable market revenue (or losses) are calculated by subtracting the operational costs from the strike price (Bezerra et al., 2006; Bezerra, Barroso, & Pereira, 2011). This implies the strike price is the highest price the capacity provider can receive in the market. This does not have to be true since it might be possible the market reference price is not related to the market where the capacity provider is active. For example, the market reference price could be the day-ahead market price, and the capacity provider receives revenue from ancillary services. The ancillary service market prices are relatively higher compared to day-ahead market prices (Regelleistung, n.d -a.; EPEX SPOT, n.d. -a). This means the capacity provider can earn more than the strike price imposed by the TSO if the reference price is based on the day-ahead market price.

Based on outdated costs of EES technologies, lack of specific focus on the European reliability options mechanism and the role of storage, no conclusion can be drawn as to whether EES is competitive in the future Belgian capacity market. The findings of this study for Belgium could help capacity providers in different countries whether they should participate in an auction of a central buyer mechanism based on reliability options.

Table 2 presents the current state of scientific knowledge on the relevant subjects for evaluating the competitiveness of EES in the future Belgian capacity market.

Subject	Scientific knowledge <i>None - little – sufficient – much</i>	References
Central buyer mechanism based on reliability options	Sufficient	Bidwell (2005), Vázquez, Rivier, & Pérez-Arriaga (2002), De Vries (2007), Vázquez, Batlle, Rivier, & Pérez-Arriaga (2003), Bezerra et al. (2006), Bezerra, Barroso, & Pereira (2011)
Role of EES and increasing (intermittent) RES capacity	Much	Ferreira, Garde, Full, Kling, & Lopes (2013), Soloveichik, (2011), Dunn, Kamath, & Tarascon, (2011), Ibrahim, Ilinca, & Perron (2008), Divya, & Østergaard (2009)
Contribution of EES to the security of supply	Sufficient	Zhou, Mancarella, & Mutale (2015), Konstantelos, & Strbac (2018), Evans, Tindemans, & Angeli (2019), Sioshansi, Madaeni, & Denholm, (2013)
Competitiveness (in central buyer mechanism based on reliability options)	Little	Vázquez, Rivier, & Pérez-Arriaga (2002) Bezerra et al., (2006), Bezerra, Barroso, & Pereira (2011)
Market rules for EES participating in capacity auctions	None	

Table 2. Current state of scientific knowledge on the relevant subjects for evaluating the competitiveness of EES in the future Belgian capacity market.

3. Research questions and approach

3.1 Research questions

Based on the identified knowledge gap and research objective, the main research question of the research can be formulated as follows:

What is the competitiveness of electrical energy storage in the future Belgian capacity market?

And the following sub-questions need to be answered to answer the main research question:

1. What are the characteristics of the Belgian Capacity Remuneration Mechanism?
2. Which EES technologies fit the characteristics of the Belgian capacity market best?
3. What is the revenue derived from the wholesale electricity market and the potential payback obligation of the capacity remuneration mechanism?
4. What is the revenue derived from ancillary services?
5. What is the remuneration required for EES in Belgian capacity remuneration mechanism auction?

3.2 Research approach

The research objective is to evaluate the competitiveness of EES in the future Belgian capacity market by providing a systemic view of the problem. The first two sub-questions of this study are qualitative in nature, and the last three sub-questions are quantitative in nature. The relevant methodology to fulfil the objective of this study and answer the research questions is *mixed methods research*. Mixed methods refer to the integration, or ‘mixing’ of both qualitative and quantitative data in one study. The idea behind the methodology is that the combination of qualitative and quantitative approach leads to a better understanding of the research problem than only one of the two approaches is applied (Creswell, 2014). The relevant research approaches and research methods used in this study will be discussed per sub-question.

What are the characteristics of the Belgian Capacity Remuneration Mechanism?

The question results in an overview of the Belgian CRM characteristics. The characteristics will be identified through literature review and desk research. Literature can help to understand the general functioning of CRMs. Desk research includes research reports, consultation documents, and Belgian and European laws and legislations from actors such as the CREG, Elia, the Belgian government and the European Commission.

Which EES technologies fit the characteristics of the Belgian capacity market best?

The most suitable EES technology in the future Belgian capacity market, and taken into consideration in this research will be treated with the above question. Literature review and desk research are suitable methods for identifying appropriate EES technologies in the Belgian capacity market. Literature is relevant for comparing the characteristics of the different EES technologies. Desk research includes studies on storage costs of energy research agencies and reports on the suitability of specific technologies in Belgium.

What is the revenue derived from the wholesale electricity market and the potential payback obligation of the capacity remuneration mechanism?

First, the wholesale electricity market with the greatest economic potential for the considered EES technology from the previous sub-question will be determined. Subsequently, the potential revenue and payback obligation are calculated under different CRM design and price scenarios. The relevant research methods are desk research for creating electricity market and payback obligation scenarios. The expected intraday market income is assessed by the software tool Linny-R which applies the optimization technique linear programming. Historical wholesale electricity market prices obtained via Eneco will be used as input of the optimization model. The scenarios will be further discussed in the 5.6 and Linny-R in 3.3.2.

What is the revenue derived from ancillary services?

Similar to the previous sub-question, the ancillary service with the greatest economic potential for the considered EES technology will be determined. The potential revenue will be calculated again under different CRM design and price scenarios. The appropriate research method is desk research for creating ancillary service price scenarios, and Excel will be used for analysing historical FCR prices and making relevant calculations. Historical FCR prices are obtained from the ancillary services auction platform Regelleistung.

What is the remuneration required for EES in Belgian capacity remuneration mechanism auction?

Eventually, the required capacity remuneration will be calculated and based on the revenue from the wholesale market or ancillary services, storage costs and the payback obligation. The required capacity remuneration will be determined by Excel-based financial modelling, using the Net Present Value (NPV), which will be further explained in 3.3.1.

3.3 Methods

3.3.1 Net Present Value

Financial modelling is a meaningful methodology for decision-makers to offer business solutions (Ho, & Lee, 2004). The financial modelling method Net Present Value (NPV) is chosen to investigate the economic competitiveness of BES. The method is the most commonly used for evaluating investments. The NPV is the sum of the cash inflows and outflows discounted to the present values (Arnaboldi, Azzone, & Giorgino, 2014).

The formula of the NPV in this research is presented below. The income and costs are calculated at each point in time t over timespan N and discounted at the discount rate r_r (Belderbos, Delarue, & D'haeseleer, 2016). The cash flows taken into consideration in this research include the earnings before interest, taxes, depreciation, and amortisation (EBITDA) and the corporate tax. Thus, income revenue derived in the electricity market R_{market} , the capacity remuneration R_{crm} , operations and maintenance (O&M) costs for BES $C_{o\&m}$ and possible costs arising from participating in the CRM C_{crm} . The capital expenses (CAPEX) I_0 are not discounted to today's values in this research. The size of the storage project in this research can be realized within a year. The total capital expenses (CAPEX) of the EES system will be made at the beginning of the project ($t = 0$) and there is no debt financing required. Therefore, CAPEX are not discounted (Arnaboldi, Azzone, & Giorgino, 2014). A positive NPV will result in a net profit which means the investment is acceptable. On the other hand, a negative NPV will result in a net loss, and the investment should be rejected (Arnaboldi, Azzone, & Giorgino, 2014).

$$NPV = -I_0 + \sum_{t=1}^N \frac{R_{market} + R_{crm} - C_{o\&m} - C_{crm} - C_{tax}}{(1 + r_r)^t}$$

The required capacity remuneration can be derived by complying with the condition that the NPV should be greater than 0.

3.3.2 Linny-R

The expected wholesale market income is assessed by the software tool Linny-R which applies the optimization technique linear programming. Linear programming involves the minimising or maximising a linear objective function given certain equality and equality constraints (Karloff, 2008). The program, developed by Dr. P.W.G. Bots, determine the most appropriate operation schedule of BES in order to maximize profit (Henriques, & Stikkelman, 2017). Thus, it calculates the optimal moments of buying and selling electricity in the wholesale market. The objective function is shown below and is subject to a set of constraints shown in Table 3.

$$\max \sum_{t=1}^T P_t * ID_t$$

Constraints	Description
T	Planning horizon
$P_t > 0$	Charging power P at hour t
$P_t < 0$	Discharging power P at hour t
$E_{t+1} = E_t + \eta * P_t * h$	Energy capacity stored expressed for charging ($P_t > 0$) at hour t and roundtrip efficiency η
$E_{t+1} = E_t + P_t * h$	Energy capacity stored expressed for discharging ($P_t < 0$) at hour t
ID_t	Wholesale market price at hour t
$-P_{max} \leq P_t \leq P_{max}$	Charge-discharge power capacity at hour t should be less than the maximum power capacity of the BESS
$0 \leq E_t \leq E_{max}$	Charge-discharge energy capacity at hour t should be less than the maximum energy capacity of the BESS

Table 3. Set of BESS constraints and description (Hu, Chen., & Bak-Jensen, 2010).

The optimisation of the charge-discharge decisions, and so the prediction of the wholesale market income, in Linny-R is based on the rolling horizon approach (Bots, 2017). The approach uses currently known information and short-term forecasts which has a higher level of reliability to solve the optimisation problem while retaining the effectiveness of the calculation (Lu, Ying, & Chen, 2016). The rolling horizon approach is commonly used for scheduling problems dealing with uncertainty such as inventory control and traffic forecasts (Silvente, Kopanos, Dua, & Papageorgiou, 2018; Lu, Ying, & Chen, 2016).

The rolling horizon approach is shown in Figure 3. The total planning horizon T is split up into N stages where each stage n contains m intervals (where $m \geq 1$). Each stage n consists of a roll period l , which represents reliable (short-term) forecasts and a look-ahead period $m - l$ which represents less reliable (medium-term) forecasts. The model computes successive stages the roll period l while taken into account the entire stage n . Thereafter, the stage n moves forward by l time steps until stage $n + 1$, both forecasts will be updated and the procedure is done for all N stages. It should be taken into consideration that longer optimisation periods, and in particular longer the look-ahead periods, which consists of medium-forecasts, decrease the reliability of the overall prediction (Lu, Ying, & Chen, 2016).

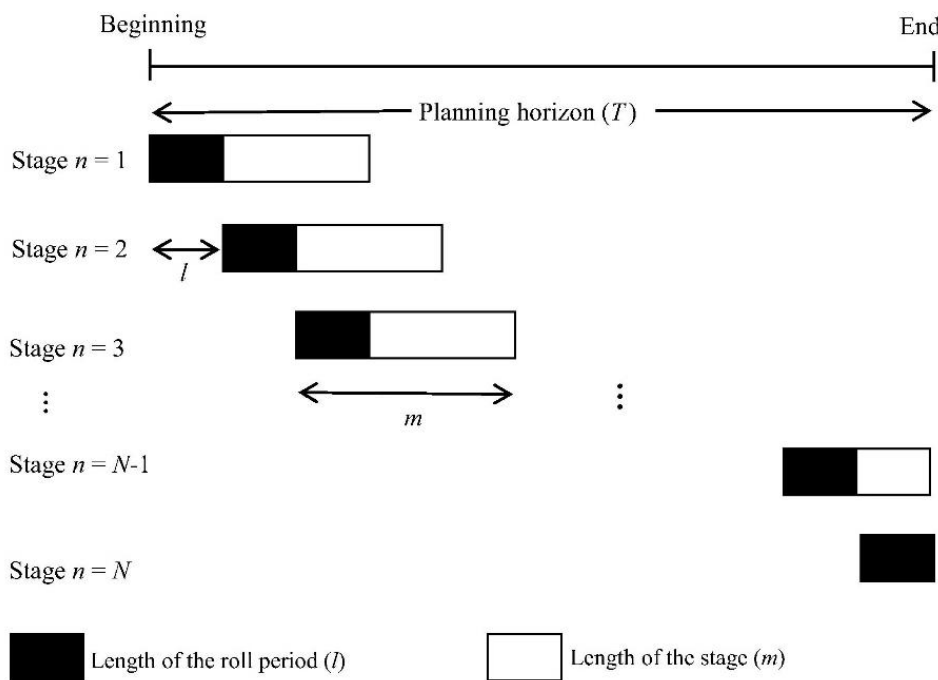


Figure 3. Rolling horizon approach (Lu, Ying, & Chen, 2016).

4. System description

This chapter will first describe the characteristics of the Belgian CRM based on what is known is so far. Thereafter the appropriate EES technologies on the Belgian capacity market will be discussed. Lastly, the chapter describes the Belgian wholesale electricity market and ancillary services and focusses on relevant market developments.

4.1 Characteristics of the Belgian CRM

The Belgian bill regarding the CRM has been adopted on April 4, 2019 (Belgische Kamer van volksvertegenwoordigers, 2019a). The Belgian CRM should comply with the European Union state aid rules, and the European Commission is expected to approve the mechanism in June 2020. The prequalification period starts June 2021, and the first auction (T-4) is planned in October 2021 to ensure sufficient capacity from November 2025 (Elia, 2019i; Elia, 2019d). Figure 4 presents the timeline until the first capacity auction of the Belgian CRM. It can be concluded from the timeline that the final CRM market rules and auction parameters will be published after writing this research. Therefore, this section describes first the characteristics of the Belgian CRM from what is known from the bill and reports from Elia meetings. It focusses on the most important parameters within the scope of this research for determining the competitiveness of EES. Subsequently, assumptions will be made for these parameters based on proposals from CRM Task Force (stakeholder) meetings organized by Elia, CRM design notes and parameters from European Commission approved CRMs in the United Kingdom, Ireland, Italy and Poland (Elia, 2019h; European Commission, n.d.).

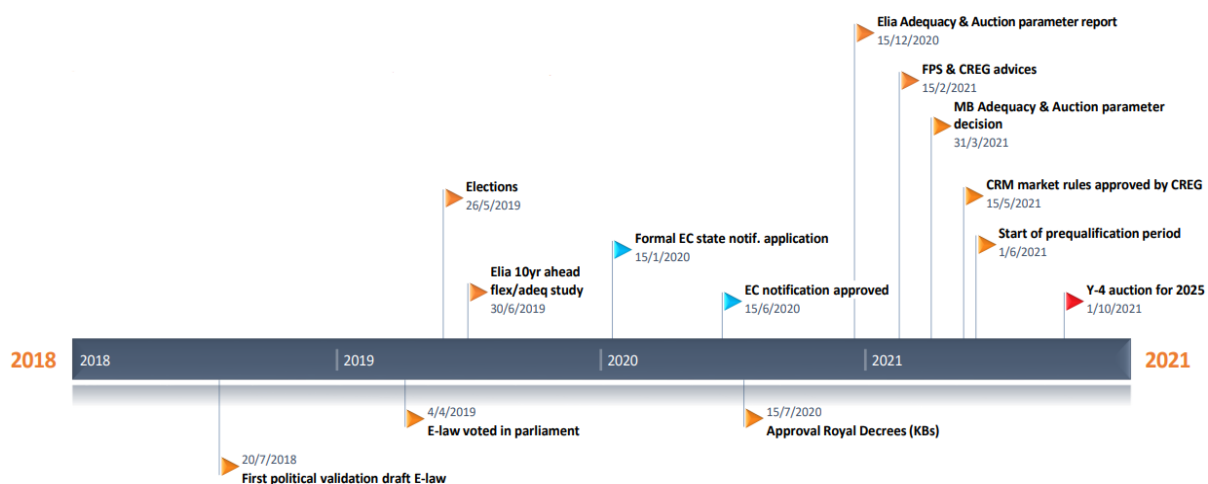


Figure 4. Belgian CRM timeline until the first capacity auction (Elia, 2019i).

4.1.1 Description

The capacity auction of the CRM is a competitive process in which capacity providers offer a price for the provision of capacity. Capable capacity providers are existing and future electricity generators, storage facilities, demand-side response and foreign capacity (Belgische Kamer van volksvertegenwoordigers, 2019a). Two auctions will be organized by Elia for each capacity delivery period: one auction four years ahead of each delivery year (T-4 auction) and one auction a year ahead of each delivery year (T-1 auction). Elia is responsible for the annual determination of the capacity required and the auction parameters for the T-4 and the T-1 auctions, whereas the CREG monitors the CRM. The volume report consists of the calculations of the total capacity required and the number of hours during which the capacity will be used for the sake of adequacy to ensure the security of supply. The parameter report includes the demand curve, price limit(s), market reference price, strike price, and de-rating factors.

Table 4 provides an overview of the most important elements of the CRM that determines the functioning. All the features will be described shortly.

Product design	Auction design	Economic parameters demand curve	Volume assessment
Market reference price	Clearing algorithm	Demand curve (y-axis)	Demand curve (x-axis)
Strike price		Price/bid caps	T-1 reserved volume
Availability requirements			De-rating factors
Availability penalties			Investment levels
			Minimum participation threshold

Table 4. Elements determining the functioning of the CRM (Elia, 2019i).

4.1.1.1 Market reference price and strike price

The CRM proposed in Belgium is based on reliability options. A reliability option is a call option and refers to the contract that includes the obligation of the capacity provider to pay the option buyer the positive difference between of the market reference price p and the strike price s for the capacity sold under the contract. In return, the capacity provider receives a fixed premium fee. The conditions mentioned above apply during the contract period of the call option and are independent whether the capacity provider is trading electricity in the spot market. The purchaser of the reliability option, which is the TSO Elia, pays the market reference price p and receive the difference between $p - s$ if $p > s$. This means if $p > s$, the net payment is s and the maximum price for the purchaser is capped at the strike price s . The reliability option allows buying at p , but when $s > p$ the purchaser will buy rationally at the market reference price p . Capacity providers limit the highest possible price from p to s by selling reliability options. In other words, capacity providers change their fluctuating revenue to a fixed revenue, and therefore reducing their income risk. Choosing for reliability options might be interesting for capacity providers dealing with fluctuating revenue, e.g., peak plants. As mentioned above, the payback obligation when $p > s$ is independent whether the capacity provider is trading electricity on the spot market. If the capacity provider cannot deliver the demand required while not trading on the energy market, the payback obligation with the reliability option is $(p - s)$ (Vázquez, Rivier, & Pérez-Arriaga, 2002).

Figure 5 shows the development of the market reference price (here spot price) over time and the imposed strike price. $s > p$ is true in $t1$ and $t5$, whereas $p > s$ is true in $t2$, $t3$ and $t4$. $t3$ illustrates the period where the capacity provider fails to deliver the contracted capacity (Vázquez, Rivier, & Pérez-Arriaga, 2002).

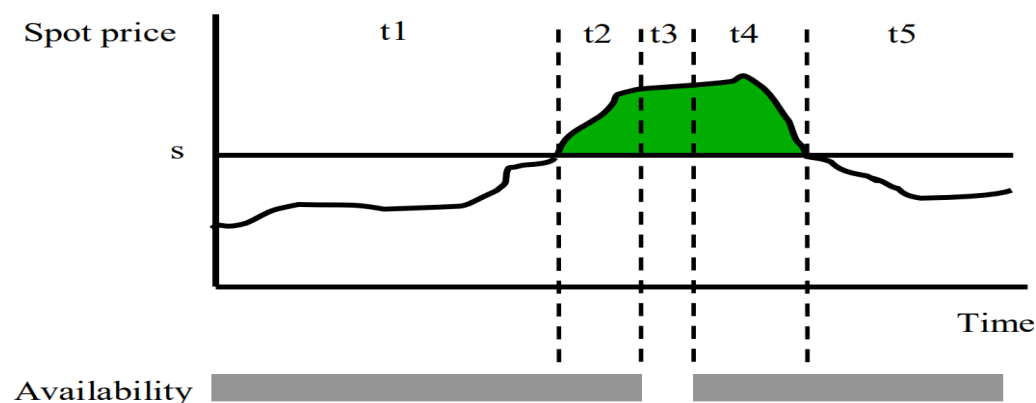


Figure 5. Application of reliability options (Vázquez, Rivier, & Pérez-Arriaga, 2002).

The different outcomes of the reliability mechanism for the buyer of capacity and the capacity provider are indicated in Table 5.

Time	T1	T2	T3	T4	T5
Demand pays (€/MWh)	p	$p - (p - s) = s$	s	s	p
Capacity provider receives (€/MWh) <i>Excluding reliability option</i>	p	p		p	p
Capacity provider receives (€/MWh) <i>Including reliability option</i>	p	$p - (p - s) = s$	$-(p - s) - pen$	s	p

Table 5. Possible outcomes reliability options (Vázquez, Rivier, & Pérez-Arriaga, 2002).

Reliability options should limit windfall profits and increase the availability incentive during moments of (imminent) scarcity. Imminent scarcity moments and moments when the market reference price p exceeds the strike price s are highly correlated. This provides an incentive for capacity providers to be active in the energy market during moments of (imminent) scarcity (Elia, 2019f).

The equation below describes the payback obligation to the TSO if the market reference price exceeds the strike price. The payback obligation is equal to the market reference price minus the strike price ($p - s$) times the number of hours t to which $p > s$ is true. (Vázquez, Rivier, & Pérez-Arriaga, 2002).

$$C_{crm} = \int_{p>s} (p - s) * C dt \quad (8)$$

- C_{crm} Costs arising from participating in the CRM [€/year];
- p Market reference price [€/MWh];
- s Strike price [€/MWh];
- C Obligated capacity, i.e., installed capacity times the corresponding de-rating factor [MW].

According to Elia's proposal for the Belgian CRM, the market reference price 'represents a continuous and relevant energy (spot) price signal (€/MWh) of the Belgian power market revenue, and capturing moments relevant for the security of supply' (Elia, 2019f, p. 4). The Belgian day-ahead market price has been proposed as the market reference price because of its liquidity. The price signal is closely related to the (near) scarcity moments, and all technologies can react to the price. No alternatives have been proposed during the CRM Task Force stakeholder meetings organised by Elia. Therefore, the Belgian day-ahead market price will be considered as the market reference price in this research (Elia, 2019g; Elia, 2019f).

One single strike price will be applied in Belgium according to the latest CRM design notes (Elia, 2019m). The strike prices of European reliability options CRMs are taken into consideration. Both strike prices of the Italian CRM and the Irish all-island CRM are taken into consideration. Table 6 shows the strike price of the Italian CRM and the Irish all-island CRM. In Italy, the strike price proposed is equal to the variable costs of the peak technology on the energy market. In the latest proposal, it was the variable costs of an Open Cycle Gas Turbines plant (OCGT), which was € 125/MWh (European Commission, 2018). The strike price in Irish all-island T-4 capacity auction 2022-2023 was € 500/MWh (EirGrid, & SONI, 2019c). Both strikes prices will be taken into account in the scenarios.

CRM	Strike price [€/MWh]
Italy	125
Irish all-island	500

Table 6: Mentioned strike prices in Italy and Irish all-island CRM (European Commission, 2018; EirGrid, & SONI, 2019).

4.1.1.2 Availability requirements and availability penalties

All awarded capacity providers in the CRM auction contribute to the adequacy in Belgium. Elia monitors the availability of each capacity provider during ‘adequacy relevant moments’ in the contracted period. The Availability Monitoring Trigger (AMT) to identify these adequacy relevant moments, i.e., AMT moments, is the Belgian day-ahead market price. The availability monitoring of the contracted capacity providers is triggered if the Belgian day-ahead market price exceeds a yearly defined AMT price. Every hour the availability monitoring is triggered is called an AMT hour, and consecutive AMT hours is called an AMT moment (Elia, 2019k).

Storage, aggregation of demand response and emergency assets capacity providers are energy-constrained, so situations occur in which the AMT moment lasts longer than the capacity provider’s (energy) reservoir constraint. Therefore, their contribution towards adequacy is determined in a Service Level Agreement (SLA). The SLA is based on the capacity’s energy constraint, i.e., maximum storage depth. The capacity provider should provide according to the SLA their capacity until the energy reservoir of its asset is exhausted. Hereafter, there is no delivery obligation for the capacity provider anymore for that day since the limit is one activation per day. Table 7 shows the different SLA categories for energy-energy constrained capacity providers and corresponding energy delivery duration. As an example, if the storage depth of an asset is one hour, e.g., EES power and energy capacity dimensioning is 10 MW/10 MWh, it should deliver only during one AMT hour per day the (contracted) obligated capacity (Elia, 2019k).

Category	Duration [hour]	Limit [activation/day]
SLA #1	1	1
SLA #2	2	
SLA #3	3	
SLA #4	4	
SLA #5	8	
SLA #6	∞	

Table 7. SLA categories for energy-constrained capacity providers. Adapted from Elia (2019k).

Differences between the capacity provider's available capacity and the obligated capacity, i.e., missing capacity, could occur because of planned or forced outages (Elia, 2019k). Capacity providers should cover the additional capacity required in a secondary market. Elected bids from capacity providers could be (partly) transferred to other prequalified capacity providers of the capacity auction with excess capacity of the capacity auctions for a certain period and price. Capacity providers are penalized if they cannot cover the missing capacity in the secondary market (Elia, 2019j).

The secondary market is considered as a liquid market. It is assumed in this research that the capacity required to meet the contracted availability requirement is always met by capacity from the secondary market. Besides, the Belgian CRM does not exclude any form of capacity in the auctions because of the European Commission's technological neutrality requirement. EES is even mentioned as an example in Elia's CRM presentation (Elia, 2019i). Therefore, the availability requirement to participate in the capacity auctions will be most likely no issue for EES. Last, the expected high penalties provide a financial incentive to comply with the capacity delivery obligation. Therefore, payback obligation in terms of penalties is not taken into consideration.

4.1.1.3 Clearing algorithm

The capacity remuneration is a yearly fixed premium in euro per MW. The pricing depends on the type of CRM design. In the pay-as-bid design, the capacity provider receives the accepted bid price in the auction whereas in the pay-as-clear design all capacity providers receive the same market-clearing price (Harbordm & Pagnozzi, 2014).

The pay-as-bid design will be applied to the first two CRM auctions, i.e., the T-4 auction in 2021 and 2022, and the pay-as-clear design will be applied in both T-1 and T-4 subsequent CRM auctions.

4.1.1.4 Demand curve and price caps

The demand curve describes the volume, i.e., capacity, to be contracted as a function of the price per MW per year. The curve is often defined by three points, each representing the willingness to pay for a certain level of security of supply. One point on the curve corresponds to the minimum capacity which should be contracted at a certain price cap, i.e., maximum price bid. The second point represents the price and capacity required to ensure the desired security of supply level. The last point represents the maximum capacity which could be contracted at zero euro per MW. Elia computes the capacity required each year based on different scenarios and sensitivities. No further details have been published yet regarding the demand curve (Elia, 2019l).

4.1.1.5 T-1 reserved volume

The volume required for the T-4 auction is based on the desired security of supply level. The T-1 auction is used for the refinement of capacity supply and demand. The minimum reserved volume is at least equal to the capacity that has, on average less than 200 operating hours per year to cover the total peak capacity (Belgische Kamer van volksvertegenwoordigers, 2019a).

4.1.1.6 Minimum participation threshold

The minimum capacity participation threshold, after applying de-rating factors, under which capacity providers cannot participate in the prequalification process and therefore, in the capacity auction (Belgische Kamer van volksvertegenwoordigers, 2019a).

4.1.1.7 De-rating factors

The CRM should contract the capacity to provide a secure energy supply. However, generation units, demand response providers and storage facilities are assumed not always to be able to continuously deliver 100% of their of generation capacity due to malfunctions, lack of energy capacity, maintenance or weather conditions. In the Belgian CRM, the contribution of a technology or a unit within “near scarcity” hours is reflected by de-rating factors. Near scarcity is the situation where the national resources and import could just meet the country’s electricity demand. Market price thresholds determine the near scarcity hours (Elia, 2019e). The system is considered adequate when the capacity can meet the load demand anytime, given a certain reliability standard (Elia, 2019k). The de-rated capacity participating in the CRM auction, which is the contribution to adequacy, is equal to the nominal capacity times the relevant de-rating factor for the capacity provider.

Each SLA category as presented in Table 7 will correspond to a specific de-rating factor. The de-rating factor represents the contribution of an asset in the SLA category to the adequacy in Belgium. No concrete de-rating factors have been proposed in Elia’s CRM meetings yet. However, the first SLA category is 1-hour duration (Elia, 2019e). Thus, the minimum storage depth of the BESS should be at least 1 hour to be rewarded in the Belgian CRM.

The de-rating factors of the upcoming Italian reliability options mechanism have not been published yet. Table 8 shows the de-rating factors of storage (excluding hydro storage) in the T-4 capacity auction delivery year 2022-2023 in the United Kingdom's CRM and the Irish all-island's CRM. The de-rating factor is dependent on the maximum storage duration of the asset, which is the ratio power capacity/energy capacity. The greater the storage duration, i.e., the relatively larger the energy capacity compared the power capacity, the more capacity is awarded in the capacity auction. Table 8 also includes the de-rating factor of the Polish capacity auctions in 2018 for the delivery year 2021-2022, 2022-2023 and 2023-2024. Striking is the minimum duration of storage in Poland of 4 hours.

CRM	De-rating factor 1h storage depth [%]	De-rating factor 2h storage depth [%]	De-rating factor 4h storage depth [%]
United Kingdom	29,4%	56,68%	80%
Irish all-island	39,4%	59,9%	70,2%
Poland	n/a	n/a	96,11%

Table 8. United Kingdom and Irish all-island De-rating factors T-4 capacity auction (deliver year 2022/23) and Poland de-rating factors capacity auction (delivery year 2021-2022, 2022-2023, 2023-2024) (Rozporządzenie Ministra Energii; 2018; EirGrid., & SONI, 2019; National Grid, 2018c).

4.1.1.8 Investment levels

The standard CRM contract is for a delivery period of one year. Depending on the investment costs, both Belgian and foreign capacity providers may be eligible to a maximum of 3, 8 or 15-year CRM contracts. Investments thresholds distinguish the different contract periods and thus the capacity remuneration. The objective of the different investment levels is to create a level playing field among potential capacity providers with different investment costs (CREG, 2019).

The CREG has mapped the investment thresholds of European CRMs and presented in Table 9 It is striking that the investment threshold for a delivery period of 15 years differs greatly per country (186.000 – 705.882 €/MW). The CRM contract duration relevant for this research will be explained in 5.5

CRM	Delivery period [years]	Investment threshold [€/MW]
United Kingdom	1	n/a
	3 (T-4 auction 2018)	152.550
	15 (T-4 auction 2018)	305.100
Irish all-island	1	n/a
	Max. 10	300.000
Poland	1	n/a
	5 (7 If CO ₂ < 450kg/MWh)	117.647
	15 (17 If CO ₂ < 450kg/MWh)	705.882
Italy	1	n/a
	15	186.000

Table 9. Investment levels of European CRMs (CREG, 2019).

4.1.2 Conclusions

The availability requirements and the availability penalties are relevant parameters to consider since strict requirements and penalties can be a barrier to entry to the capacity auction. However, both do not seem to cause any problems regarding participation in the CRM auctions. Given the research objective, the clearing algorithm, demand curve, price caps, and the T-1 reserved volume are beyond the scope of this research and not taken into consideration. The market reference price and strike price are the fundamentals of a CRM based on reliability options. The potential costs arising from the payback obligation might have a significant impact on the competitiveness of EES. Besides, the de-rating factor directly influences the capacity remuneration of EES and therefore the competitive. The investment levels are related to the number of capacity delivery periods and thus the period for which the capacity provider receives remuneration.

To conclude, the most important CRM auction parameters in this research for evaluating the competitiveness of BES are the reference price, strike price and the de-rating factors.

4.2 Appropriate EES technologies

Much research has been conducted into large-scale electrical storage. Studies from CREG (2015) and FOD Economy (2015) and literature on EES discussed in 2.3 could provide insights into the different EES technologies. The technologies taken into consideration are Large-scale Pumped Hydroelectric Energy Storage (PHES), Compressed Air Energy Storage (CAES), Flywheel Energy Storage (FES) and Battery Energy Storage (BES).

PHES and CAES are mainly used for energy time-shifting because of the low energy costs, low self-discharge rates and the ability to charge and discharge economically optimally over many hours (up to 40 hours is not exceptional) (IRENA, 2017). However, PHES and CAES deal with geographic restrictions because PHES needs significant differences in height between two reservoirs and CAES needs underground cavern reservoirs to store compressed air. Both requirements cannot be met in Belgium due to lack of space for PHES and no feasible geographical resources for CAES (Limpens, & Jeanmart, 2018).

FES has several benefits such as allowing a high number of charge-discharge cycles, providing high power capacity and fast response time (Pena-Alzola, Sebastián, Quesada, & Colmenar, 2011). However, the energy installation costs of FES is significantly higher compared to PHSES, CAES and Li-ion batteries (respectively 140, 56 and 7 times higher in 2016 and still is towards 2030). Also, the technology deals with self-discharge rates of 15% per hour and therefore less suitable for energy time-shifting (IRENA, 2017).

Lithium-ion (Li-ion) storage, which is a type of Battery Energy Storage (BES), is an emerging technology in the utility-scale energy market and has several advantages over other technologies. Major technical benefits of Li-ion batteries are the short response time, high power and energy density, and high round-trip efficiency (Luo, Wang, Dooner, & Clarke, 2015). From an economic perspective, the price of an average Li-ion battery pack dropped 85% from 2010 to 2018. According to the historical battery pack prices between 2010 and 2018, BloombergNEF (2019a) computed a learning curve of 18%. This means every doubling of the cumulative volume of Lithium-ion battery packs decreases the price by 18% and results in an average Li-ion battery pack price is \$ 62/kWh in 2030 (BloombergNEF, 2019a). The Li-ion battery pack price outlook until 2030 is shown in Figure 6.

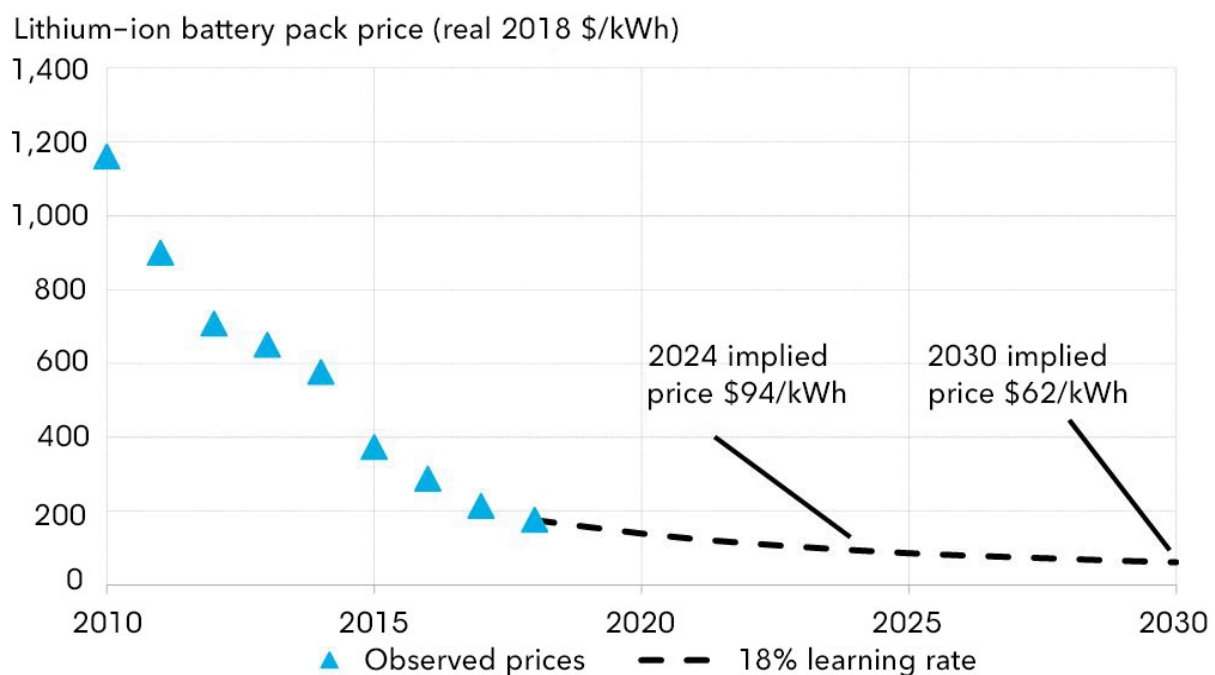


Figure 6. Price development of Li-ion battery pack price outlook till 2030 (BloombergNEF, 2019a).

However, battery price forecasts should be interpreted with caution. BloombergNEF (2019b) predicted four months after the price forecasts in Figure 6 an average price of \$ 88/kWh in 2030 (~ 40% difference in price prediction four months). In addition to the strong price reduction, Li-ion storage is often preferred for fast frequency related ancillary services because of its fast response time.

Eneco has also investigated the most suitable EES technologies for less than three hours of storage duration applications in 2019. The research concludes that less than three hours storage duration with Li-ion batteries, focussing on the FCR, imbalance, and intraday market, might be the most economically feasible (Eneco, personal information, May 2, 2019).

Based on research from IRENA (2017), BloombergNEF (2019a) and Eneco (personal information, May 2, 2019), the focus of this research will be specifically on Battery Energy Storage (BES), in particular, Li-ion storage. Li-ion storage will hereafter be referred to as BES or Battery Energy Storage System (BESS) when the entire system is described. The chemistry choice for the Li-ion BES is nickel-manganese-cobalt (NMC) because of the favourable combination of characteristics such as performance, safety, and costs (IRENA, 2017). NMC Li-ion cells are used as well in Eneco's 48 MW BES system in Jardelund Germany and provide frequency control reserve to maintain the network frequency (Eneco, 2018; Eneco, personal information, August 2, 2019).

4.2.1. Common BES projects

There are several BESS active on energy markets, varying in power capacity and energy capacity. In the United Kingdom, three kinds of BES projects trends, differing in power capacity size and application, have been identified over the past years and is coming up (Energy Storage News, 2019). The first category includes utility-scale stand-alone 50 MW BES projects with long duration capacity contracts and income derived from energy markets. Second, 10-20 MW BES projects in combination with (renewable) generation assets such as wind and solar. Last, smaller-scale projects active in the Commercial & Industrial (C&I) sector also in combination with generation assets.

4.3 Opportunities in the electricity markets

This section describes the opportunities for BES in the Belgian electricity market. First, the Belgian wholesale electricity markets and the ancillary services offered by Elia will be explained shortly in the description section. Subsequently, the technical feasibility and the revenue potential of BES in the electricity market will be considered in the analysis section.

4.3.1 Wholesale electricity market

4.3.1.1 Description

The EPEX SPOT (formerly Belpex Spot Market) is the short term Belgian power exchange and operates in three market segments: the Day-Ahead Market (DAM), Continuous Intraday Market (CIM) and the Strategic Reserve Market Segment (SRM).

The DAM is the auction for daily trading of electricity the following day. Buyers and sellers submit their volume and price hour by hour, and afterwards, the supply and demand determine the hourly day-ahead price (EPEX SPOT, n.d. –b).

The CIM is the auction for continuous daily trading of electricity the same day. Trading of hourly products and several hours is possible from the day before delivery at 15:00 till five minutes before delivery (EPEX SPOT, n.d. –c). This implies the possibility to trade at 15:00 for the next day 23:00-00:00, which is 33 hours in advance. Greater price volatility is expected at the opening of the intraday trading slot because there is less certainty regarding weather conditions, what other parties are trading and other market circumstances. For example, due to fewer hours of sunshine or the wind blows less than was expected. Traders have better information about their position and prices closer to the delivery moment. Therefore, trades in the intraday market are done, on average, 5 minutes up to 8 hours ahead of the delivery moment (Eneco, personal information, July 4, 2019).

The SRM is introduced for guaranteeing the security of supply during the winter period. Elia is responsible for the design, auction, and operation of the strategic reserve (EPEX SPOT, n.d. -d). The TSO instructs contracted capacity providers during shortages to increase their load or instructs consumers to reduce their load during an activation of the strategic reserve (Elia, 2019n). Table 10 shows the main characteristics to distinguish the three Belgian market segments of the EPEX SPOT Belgium.

	DAM	CIM	SRM
Instrument series	1-hour blocks	1-hour blocks ³	1-hour blocks
Listed for Order submission	14 trading days before delivery until noon trading day before delivery	From 15:00 trading day before delivery until 5 minutes before delivery	The day before delivery for Strategic Reserve Participant; Direct Participants will have neither the possibility to submit Orders on the Belpex SRM via a different mechanism nor the possibility to cancel or modify such replicated Orders
Trading days	Every calendar day	Every calendar day	Every calendar day during the winter period
Fixing Process	Auction	Continuous trading	Strategic Reserve Allocation
Trading hours	Order book closing at 12:00	24/7	Order book closing at the publication of DAM results

Table 10. Specification of the three EPEX SPOT Belgium market segments (EPEX SPOT, n.d. -e).

³ Standard is 1-hour blocks but the blocks are freely definable (EPEX SPOT, n.d. -c).

4.3.1.2 Analysis

Figure 7 shows the Belgian day-ahead and intraday (BELPEX) distribution of the market price difference between consecutive hours for a half year between December 4, 2018, and June 4, 2019 (Eneco, personal information, June 26, 2019).

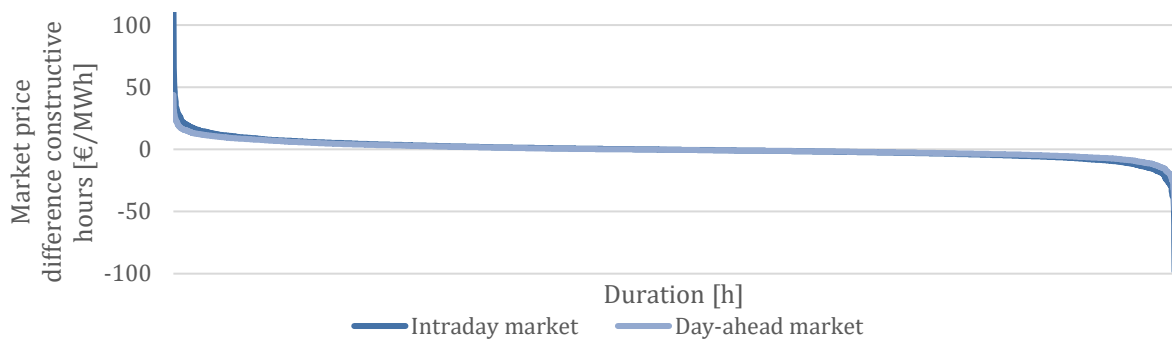


Figure 7. Sorted (high-low) difference in Belgian intraday and day-ahead prices of consecutive hours for a half year between December 4, 2018, and June 4, 2019. (Eneco, personal information, June 26, 2019).

Figure 8 focuses on the hours that occur less than 100 hours in that particular half-year. For example, during less than 10 hours this specific half-year, the price difference between consecutive hours is around € 25/MWh in the day-ahead market and almost € 40/MWh in the intraday market. The blue peak at the beginning of Figure 8 indicates greater market price volatility in the intraday market compared to the day-ahead market. EES generate income by capturing price spread in the electricity market and therefore benefits from price volatility, i.e., relative differences in market prices. This means EES' potential revenue in the Belgian intraday market is greater than the potential revenue on the Belgian day-ahead market. Therefore, the Belgian intraday market is preferred from an economic perspective and considered in this research.

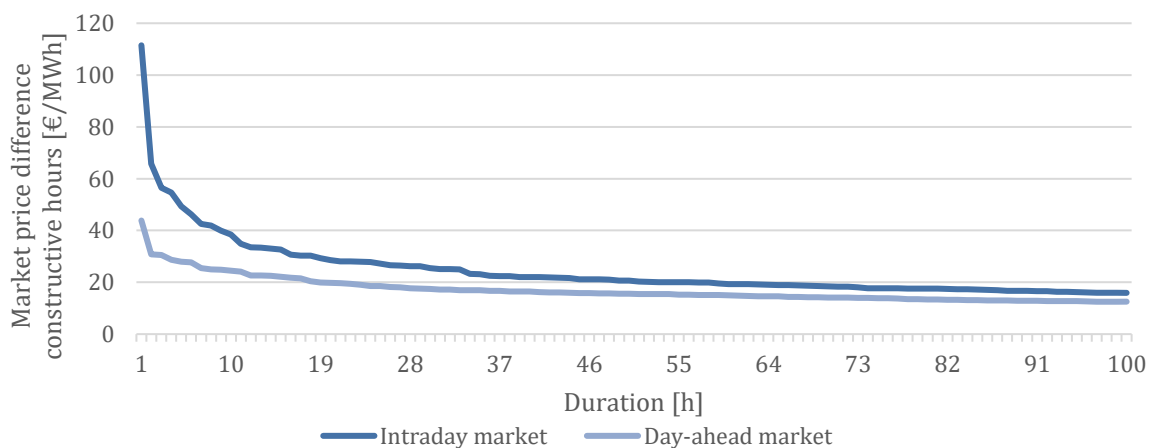


Figure 8. Sorted (high-low) difference in Belgian intraday and day-ahead prices of consecutive hours for a half year between December 4, 2018, and June 4, 2019, < 100 hours. (Eneco, personal information, June 26, 2019).

4.3.2 Ancillary services

4.3.2.1 Description

The electrical consumption must be continuously and instantaneously matched to the electricity generation. Disruptions cause deviations in the system frequency and affect the reliability of the electricity supply (Oudalov, Chartouni & Ohler, 2007). As a TSO, Elia has the responsibility to evaluate and determine yearly the volume required to maintain the reliability and of the Belgian grid (Elia, n.d. –c). Elia purchases flexible power capacity and reserves from consumers and generators connected to the grid as it does not have assets to maintain the frequency of the power grid. These services provided by consumers and generators are called ancillary services (Elia, n.d. –b).

At the moment, the European electricity market is evolving towards an integrated market consisting of various European TSOs (ENTSO-E, n.d. -a). The European guideline on electricity balancing (EBGL) has been in force in the EU since November 2017 and should increase competition, ensure the security of supply, transparency, and integration of balancing markets (ENTSO-E, 2018). Two main elements of the guideline which influence the design of the Belgian ancillary services are the notation of technological neutrality, which must lead to more technologies being able to offer ancillary services, and the short-term procurements (European Commission, 2017b). Moving from weekly towards daily procurement should increase market liquidity and efficiency (Elia, 2018b). Elia's long term vision is to create harmonised, neutral rules for the ancillary services Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserves (aFRR) and manual Frequency Restoration Reserves (mFRR) (Elia, 2019c). Deployment of multiple ancillary services by one Balancing Service Provider (BSP) is possible under certain conditions (Elia, 2018a; Elia, 2019b; Elia, 2019c).

The current ancillary services in 2019 no longer exist in the first delivery year of the first CRM auction scheduled in 2025. Therefore, the upcoming ancillary products in 2025 will be discussed, as far as known from publications from the European Network of Transmission System Operators for Electricity (ENTSO-E) and Elia. Table 11 provides an overview of the considered ancillary services, including the previous terminology, main product characteristics, and the expected date of the first procurement of the final products. Final products mean that there are currently temporary forms of the upcoming balancing products.

New terminology	Previous terminology	Activation frequency	Activation energy	Procurement
Frequency Containment Reserve (FCR)	Primary reserve (R1)	+++	+	July 2020
Automatic Frequency Restoration Reserves (aFRR)	Secondary reserve (R2)	+++	+++	July 2020
Manual Frequency Restoration Reserves (mFRR)	Tertiary reserve (R3)	+	+++	February 2020

Table 11. Overview of the (future) ancillary services (Elia, 2017a; Elia 2018d; Elia, 2019b).

One of the main implications of the European balancing guideline EBGL is moving to daily procurements for all three ancillary services. There should be auctions for six independent 4-hours blocks in a day for these three Belgian ancillary services. Elia will allow 24-hours block for aFRR providers because it fits better the technical specifications of the participating technologies. (Elia, 2018a; Elia, 2019b; Elia, 2019c). The sequence of the daily procurement cycle will be FCR, mFRR and mFRR. The different ancillary services will be discussed shortly in the following subchapters.

4.3.2.1.1 Frequency Containment Reserve

Frequency containment reserve (FCR, former 'primary reserves'), focusses on balancing the high-voltage European interconnected system. Any frequency deviations automatically activate contracted primary reserves set by the European Network of Transmission System Operators for Electricity (ENTSO-E) (Elia, n.d. -a). FCR should "stabilize the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but without restoring the system frequency and the power exchanges to their reference values" (ENTSO-E, 2009, p. 12). FCR product suppliers must reserve a capacity band (upwards and downwards) equivalent to the contracted capacity in the delivery period.

The total capacity required will be procured daily on a regional platform Regelleistung with TSO's from Germany, Austria, the Netherlands, France, and Denmark (Regelleistung, n.d. -a). The product in the auction is the FCR symmetric 200 mHz service. The provider should deliver maximum FCR power capacity between -200 mHz and +200 mHz deviation from the nominal frequency of 50 Hz and the reaction should be proportionally between -200 mHz till -10 mHz and +10 mHz till + 200 mHz (Elia, 2019b).

4.3.2.1.2 Automatic Frequency Restoration Reserve

The automatic Frequency Restoration Reserve (aFRR, former ‘secondary reserves’) takes over the responsibilities of FCR. The generation assets are activated automatically in less than 15 minutes after an imbalance incident occurs (ENTSO-E, 2009). The aFRR product is characterised by the high frequency of activations and a large amount of activated balancing capacity, as indicated in Table 11. It is considered as the most complex balancing product offered (Elia, 2018a). The aFRR provider determines a baseline (reference power), which is the power that the aFRR provider (or aggregation of providers) would have consumed or added to the grid at a certain delivery point without providing the aFRR service. The aFRR provider sends the value to Elia every four seconds. The difference between the baseline and the measured power at the delivery point is the delivered energy by aFRR provider (Elia, 2018a).

According to Elia’s aFRR design note, aFRR providers should place bids in both directions. This means, aFRR providers are obligated to bid both symmetrical, i.e., volume upwards and volume downwards, and asymmetrical, i.e., upwards or downwards (Elia, 2018a).

4.3.2.1.3 Manual Frequency Restoration Reserves

The manual Frequency Restoration Reserves (mFRR, former “tertiary reserves”) replaces and can be activated as a supplement to aFRR. MFRR is manually controlled by Elia and is normally activated for a longer period compared to FCR and aFRR (ENTSO-E, 2009).

4.3.2.2 Analysis

Table 12 summarises balancing processes availability requirements and the activation characteristics from Table 11. As mentioned in chapter 5, Li-ion batteries are characterized by their short response time, high energy density, and high round-trip efficiency (Luo, Wang, Dooner, & Clarke, 2015). Therefore, it is technically possible to develop a Li-ion BESS which meets all the balancing process requirements regarding reaction time, activation time, and the minimum time sufficient energy for full activation.

Balancing process	Maximum full reaction time	Maximum time to full activation	Minimum time sufficient energy for full activation	Activation frequency	Activation capacity
Frequency Containment Reserve (FCR)	Not artificially delayed and – as soon as possible	15 seconds (50%), 30 seconds (100%)	15 minutes (recovery of energy capacity within 2 hours after the end of the alert state)	+++	+
Automatic Frequency Restoration Reserves (aFRR)	30 seconds	7,5 minutes	4 hours (i.e., one 4-hours block)	+++	+++
Manual Frequency Restoration Reserves (mFRR)		15 minutes	4 hours (i.e., one 4-hours block)	+	+++

Table 12. Technical characteristics ancillary services (Elia, 2017a; Elia, 2018a; Elia, 2019b; Elia, 2019c).

AFRR and mFRR require capacity which can deliver four hours of energy continuously. This means a BESS should have a storage depth of at least four hours. The minimum energy delivery period of the FCR 2020 procurement has not been determined by European Network of Transmission System Operators for Electricity (ENTSO-E). The minimum activation time will be at least 15 and not greater than 30 minutes during the alert state (Elia, 2019b). The alert state is triggered by a continuous frequency deviation is greater than 100 mHz during 5 minutes or 50 mHz during 15 minutes. (European Commission, 2017c). Besides, an additional 10 minutes is required during normal state for energy-constrained capacity providers, i.e., BES, in Belgium (Elia, 2019b). In the normal state, the capacity provider is not violating the European frequency deviations rules (European Commission, 2017c). All European TSOs should assess the required minimum activation time during alert state and hand in their proposal in April 2020 (ENTSO-E, n.d. -b). At the moment, a minimum duration of 15 plus 10 minutes or 30 plus 10 minutes is equally assumable since no preference is given in Elia's proposal. Therefore, this research assumes the 'worst-case scenario' of a mandatory energy delivery availability requirement of 40 minutes.

The average price of selected bids for the considered ancillary services between January 2019 and August 2019 is shown in Table 13 (Elia, n.d. -c). FCR symmetrical 200 mHz (common auction) is the new FCR product and since July 2019 procured daily on the regional platform 'Regelleistung' (Regelleistung, n.d. -a). The weekly procurement of FCR on Elia's local (Belgium) platform will be fully procured daily on Regelleistung from July 2020. (Elia, 2019b). The participating countries on the regional platform are Austria, Belgium, France, Germany, Netherlands, and Switzerland (Regelleistung, n.d. -a; Elia, 2019b).

Table 13 shows that the average price for FCR symmetrical 200 mHz product in the regional auction is 15% lower compared to the FCR symmetrical 200 mHz product in the Belgian auction. The expectation is that the prices for R2 and R3 will also drop if R2 is auctioned on the regional platform as aFRR and R3 is auctioned as mFRR. The prices will be pressed because of the increasing volume of the joint tenders and the liquidity of the balancing market increases. Second, because of the daily procurement in the sequence FCR-aFRR-mFRR, providers try to participate in the different auctions.

This is especially true for the mFRR which the auction was first on a monthly basis. In the future, ancillary service providers can make better forecasts in the day-ahead compared to month-ahead regarding the (technical) availability, which translates into an increase of competing volume. This leads to a lower price because the premium on risk is higher in the monthly prices from uncertainty, not selling it (Elia, 2019b).

The average R3 prices (flex and standard) are already lower than the average FCR common auction price, and the average R2 price (upward/downward) might decrease to the same price as the average FCR common auction price.

Previous terminology	New terminology	Auction	Average price [€/MW/h]
R1 upward	Frequency Containment Reserve (FCR)	Belgium	2,04
R1 downward	Frequency Containment Reserve (FCR)	Belgium	1,72
R1 symmetrical 100 mHz	Frequency Containment Reserve (FCR)	Belgium	13,45
FCR symmetrical 200mHz	n/a	Common	8,84
FCR symmetrical 200mHz	n/a	Belgium	10,43
R2 upward/downward	Secondary reserve (R2)	Belgium	12,61
R3 Flex	Tertiary reserve (R3)	Belgium	4,16
R3 Standard	Tertiary reserve (R3)	Belgium	7,07

Table 13. Average price of selected bids for the ancillary services between January 2019 – week 31 August 2019 (Elia, n.d. -c).

Comparing one hour of storage depth for FCR with R2/aFRR or R3/mFRR, which requires a minimum of four hours of storage depth, the storage costs become three times as high, given the storage costs calculations in the next paragraph. However, the aFRR or mFRR revenues are not expected to be four times as high. Last, the activation frequency of R2/aFRR is higher compared to FCR as mentioned in Table 13. Thus, the higher storage costs do not outweigh any potential additional revenue. The economic concept is called 'diminishing returns'.

Therefore, this research only evaluates the ancillary service FCR symmetrical 200 mHz (common auction) and the Belgium intraday market as described in 4.3.1.

4.4 Price developments

The two sources of income of BES in this research are the intraday market and the ancillary service FCR market, as discussed in the previous section. This section discusses the future price developments of both markets.

4.4.1 Intraday market

No research has been found on the Belgian intraday market price developments. However, Elia has published in their adequacy and flexibility study average day-ahead market price forecasts in Belgium for 2020 till 2030. The price forecasts are shown in Figure 9. The model used in this study assumes all the energy is sold in the day-ahead market and the electricity price is equal to the hourly marginal price, which is based on the variable costs of the energy production facilities (Elia, 2019d). Two CO₂ price scenarios of the International Energy Agency (IEA) World Energy Outlook 2018 are taken into account (IEA, 2018). The New Policies Scenario (ref CO₂ in Figure 9) is considered as IEA's baseline scenario and takes in short countries' CO₂ emissions reduction plans and commitments into account. The scenario assumes the CO₂ price is about € 30 per tonne in 2030, which is similar to results from BNEF, HIS Markit and EU reference Scenario. The Sustainable Development Scenario (high CO₂ in Figure 9) represents, in short, the pathway to meet the Paris Agreement climate goals and the scenarios assumes a higher CO₂ price compared to the New Policies Scenario of around € 80 per tonne in 2030 (Elia, 2019d; IEA, 2018). The 'decentral' scenario assumes a capacity mix consisting of low CAPEX/high CAPEX technologies (e.g., emergency generators for load shedding, diesel generators). The 'efficient gas' scenario assumes a capacity mix consisting of new built Combined Cycle Gas Turbine (CCGT) plants and Combined Heat and Power (CHP) plants. Elia predicts gas-fired power plants will set the day-ahead market price to meet the energy demand in the future. The CO₂ price and the gas price are the main drivers of the marginal costs of gas-fired power plants, so therefore these prices have a major influence on the day-ahead market price forecasts (Elia, 2019d).

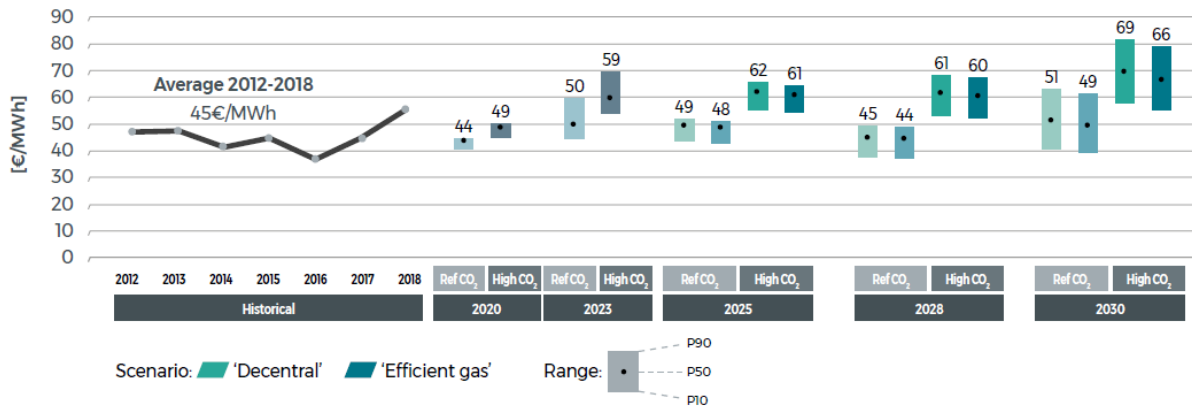


Figure 9. Average day-ahead market price forecasts in Belgium 2020-2030 under different CO₂ and technologies.

4.4.1.1 Relation between day-ahead and intraday market price

Based on multiple historical hourly intraday market prices, the Volume Weighted Average Price (VWAP) is calculated per hour. The VWAP is the weighted average price what has been paid for one MWh for a specific delivery hour. Thus, the VWAP intraday market price is close to the imbalance price if mostly all intraday market trades are made before the delivery hour. The VWAP intraday market price is determined for the random month, e.g., March in 2019. The price development has been plotted together with the Belgium day-ahead market price in figure 10. What emerges clearly from figure 10 is the same movement of the intraday price level and the day-ahead price level in the considered period. No clear trend in the intraday market price can be identified on a monthly timescale.

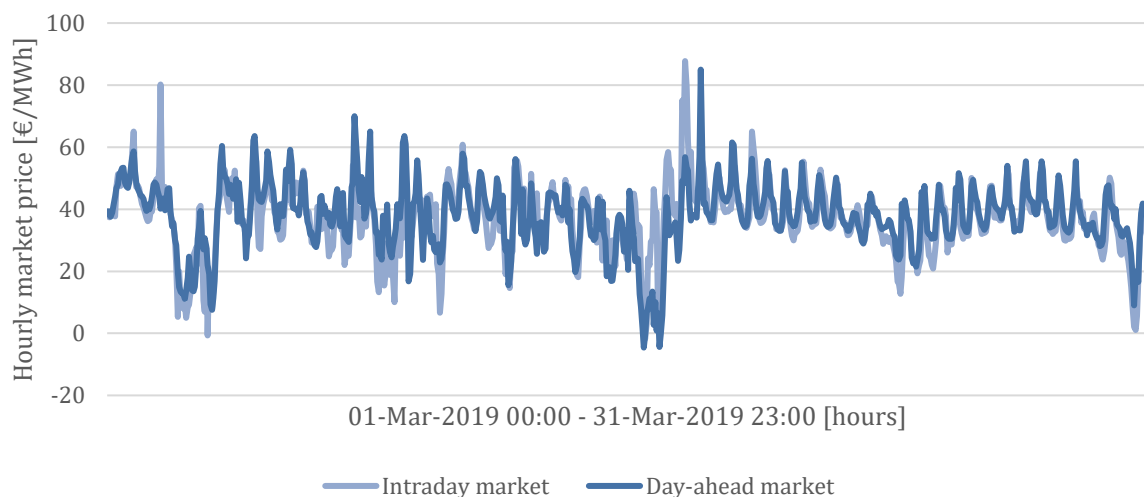


Figure 10. Hourly VWAP Belgium intraday and day-ahead market prices March 2019.

The VWAP intraday market price has also been determined on a monthly scale from January 2014 – July 2019 in Figure 11. The same movement of the Belgian intraday market and the day-ahead market is observable on a monthly level over a longer period,



Figure 11. Hourly VWAP Belgium intraday and day-ahead market prices (per month) January 2014 - July 2019.

Based on the same movement of day-ahead and intraday market prices, as shown in figure 10 and Figure 11, Elia's day-ahead market price forecasts for Belgium 2020-2030 will be used as a proxy for the future intraday market price developments.

The market prices corresponding with the New Policies Scenario (ref CO₂) will be used since this the most broadly accepted scenario by researchers and policy advisors. The average price of the 'decentral' and 'efficient gas' scenario are close together, and the average of both scenarios is taken into account.

4.4.2 FCR

There are no FCR price forecasts published by research agencies, the Belgian government or Elia. In essence, the demand, and therefore the costs and the price, of ancillary services increase by higher penetration of renewables because of its intermitted supply (Chuang, & Schwaegerl, 2009). On the other hand, the procurement of FCR and aFRR will be separated in July 2020. This means the interdependence of FCR and aFRR decrease and Elia expects an increase of bids from new entrants in the FCR market (Elia, 2018c). Also, because of the decrease in battery prices, as mentioned in 5.23, the number of new BESS projects participating in ancillary services auction is likely to increase. Also, aggregators, which aggregates small residential batteries to a large virtual battery, see ancillary services as an interesting revenue stream. For example, 90.000 BESS representing 500 MWh, which is two-thirds of the total operational BESS energy capacity online in Germany (Apricum, 2018). The rise of residential batteries may also spread to Belgium and other neighbouring countries. Elia expects the volume of the ancillary services will not significantly change in the future. Besides, more flexible generation capacity will be sourced abroad because of the further integration of the European ancillary service markets as explained in 4.3.2.1. Last, the nuclear power plants, which supplies a major part of the current Belgian power baseload, will be replaced by (to some extent) flexible generation capacity. This could lead to increased competitiveness in the FCR market and lower prices (Elia, 2019d).

5. Model description

This chapter first introduces a conceptual model of the research, which outlines all aspects that are important in determining the competitiveness of BES. Subsequently, the power and energy capacity dimensioning of the BESS will be discussed. Thereafter, the relevant approaches for modelling the FCR and the intraday market income will be taken into account. At the end of this chapter the scenarios and eventually, the experiment design will be presented.

5.1 Conceptual model

The competitiveness will be evaluated according to the constructed *competitiveness evaluation model* which has been developed for this research and presented in Figure 12. The conceptual model is based on the description of the central buyer mechanism reliability options model from PwC (2018) and the definition of competitiveness from chapter 2.4. The model aims to capture all the relevant elements that are important to consider for the decision-making process regarding participating in the CRM capacity auctions.

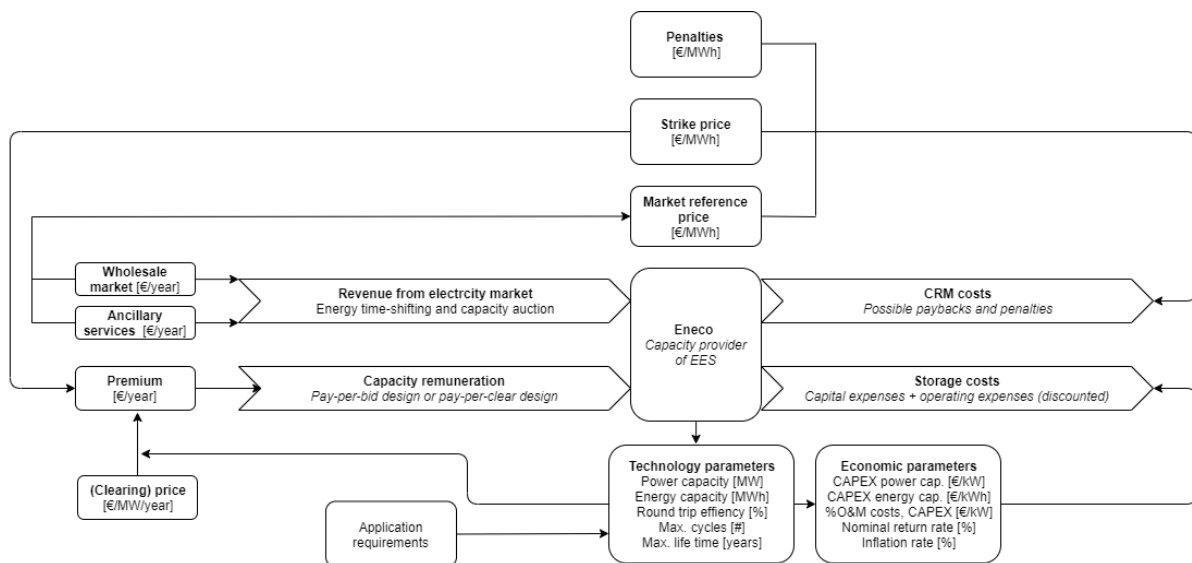


Figure 12. Competitiveness evaluation model.

5.2 BESS setup

5.2.1 Dimensioning

The initial situation in this research is a 10 MW BESS, which is a typical power capacity dimension used in the past by Irish all-island and United Kingdom's capacity auctions (CEPA, 2019; National Grid, 2018c; National Grid, 2019).

The appropriate energy capacity (MWh) for a specific power capacity depends on the application. However, according to the proposed SLA categories in 4.1.1.2, the minimum storage duration to obtain a CRM contract is 1 hour. Therefore, the minimum storage depth of the BESS would be 1 hour, so the BESS dimension would be at least 10 MW/10MWh.

The specific power and energy capacity dimension taken into consideration in this research will be discussed for a BESS operating each in the intraday and FCR market

5.2.1.1 Intraday market

Income in the intraday market is generated from energy time-shifting. For energy time-shifting, as introduced in 2.3, a greater storage depth is preferred to make optimal use of price spreads. The chosen storage depth for the intraday market are 1 hour and 2 hours. 1-hour BESS is initial setup for determining the competitiveness of BES. Although the 2-hour BESS is expected to generate more income in the intraday market, the additional income might not outweigh the additional storage costs related to the doubling of the storage depth, i.e., energy capacity. The forecasted CAPEX in 2025 would namely increase by 75% if the storage depth is doubled and the income is not likely to increase with this percentage (IRENA, 2017). More experiments will be made if a greater storage depth than 1 hour is economically profitable.

5.2.1.2 FCR market

The minimum BESS dimension is 10 MW/10 MWh. In this research the equivalent energy constraint for energy-constrained capacity providers, e.g., BES, operating in the FCR market should be at least 40 minutes as explained in 4.3.2. Given the 10 MW power capacity and the minimum 40 minutes storage duration, the required energy capacity is 6,7 MWh. In addition, energy-constrained capacity providers should increase their power capacity dimensioning by 25% to ensure continuous FCR activation (ENTSO-E, 2018a). Thus, the dimensioning of BESS operating in the FCR market should be at least 12,5 MW/6,7 MWh in order to comply with the FCR requirements. This means, 3,3 MWh is unused by the BESS. In the second BESS setup, the 3,3 MWh will be used for energy time-shifting in the intraday market.

The four BESS setups taken into consideration in the research are shown in Table 14.

Power capacity [MW]	Energy capacity [MWh]	Hours of storage depth [h]	Application
10	10	1	Intraday market
10	20	2	Intraday market
12,5	10	1	FCR
12,5	10	1	FCR + intraday market

Table 14. BESS setups taken initially into consideration.

5.2.1 Costs and technical parameters

Table 15 shows the assumptions on the Li-ion storage costs parameters and technical parameters for the years 2020, 2025 and 2030. The CAPEX, the maximum lifetime and the maximum number of cycles are based on a public report from the International Renewable Energy Agency (IRENA) (IRENA, 2017). The definition of a full cycle is further explained in appendix 12.1. The CAPEX energy and power installation costs involve all the costs of the BESS, e.g., battery pack, thermal management, controls, installation, converter, etc. (IRENA, personal communication, October 9, 2019). The percentage O&M costs, roundtrip efficiency, depth of discharge and the required rate of return are based on assumptions of Eneco (Eneco, personal information, May 21, 2019; Eneco, personal information, August 2, 2019). The Belgium inflation and euro/dollar exchange rate are based on the current rate of August 2019. The corporate tax rate is the rate in Belgium from 2020 (XE, 2019; Statbel 2019; KBC, 2018).

Parameter	2020	2025	2030
Effective CAPEX energy installation costs ⁴ [€/kWh]	326	235	169
CAPEX power installation costs [€/kW]	108	77	55
Percentage O&M costs of total CAPEX [%]	3	3	3
Roundtrip efficiency [%]	93	93	93
Depth of discharge [%]	90	90	90
Maximum full cycles [#]	2406	3031	3819
Maximum cycle life [year]	14	16	18
EUR/USD exchange rate [€/\$]	1,10	1,10	1,10
Required rate of return [%]	7,00	7,00	7,00
Inflation on O&M and commodity [%]	1,26	1,26	1,26
Belgium corporate tax [%]	25	25	25

Table 15. Li-ion BESS costs parameters and values (IRENA, 2017; Eneco, personal information, May 21, 2019; Eneco, personal information, August 2, 2019; XE, 2019; Statbel, 2019; KBC, 2018).

⁴ (nominal) CAPEX divided by the maximum depth of discharge of 90%

5.3 Intraday market income modelling

5.3.1 Description

As mentioned in 4.3.1, EES generate income by capturing price spreads in the intraday market. The operation is called ‘electric time-shifting’ and includes purchasing (charging) of electric energy when demand and energy prices are low and selling (discharging) the energy when demand and energy prices are high. (Energy Storage Association, n.d.-a). As explained in 3.3.2, the expected wholesale market income, i.e., intraday market income, is computed with the use of Linny-R. This software tool determines the most appropriate operation schedule of BES in order to maximize profit.

Figure 13 presents the visualisation of the Linny-R model for calculating the intraday market income. The different elements in the figure below can be categorized into products processes and links. The products ‘Input BE ID price 2021’ and ‘Output BE ID price 2021’ consists of the Belgium intraday market price forecasts of 2021 (8760 hours thus 8760 prices). The processes ‘Loading battery process’ and ‘Discharging battery process’ take care of the charging and discharging process whereby the battery can be charged and discharged each hour. The arrow from ‘Input BE ID price 2021’ to ‘Loading battery process’ with the value 1,08 represents the BESS roundtrip efficiency of 93%. This implies the price spread must overcome the round trip efficiency related to the charging and discharging process. The product ‘Li-ion storage’ represents the storage reservoir of the battery with a maximum storage depth of 1 hour. The storage reservoir is either full (1-hour storage) or empty (0-hour storage) in this example. Finally, the product ‘Cycle cost’ represents the fictive costs associated with the charging and discharging process and the value is equal to or smaller than zero. The product aims to reduce the number of cycles, which will be further explained in the next subchapter.

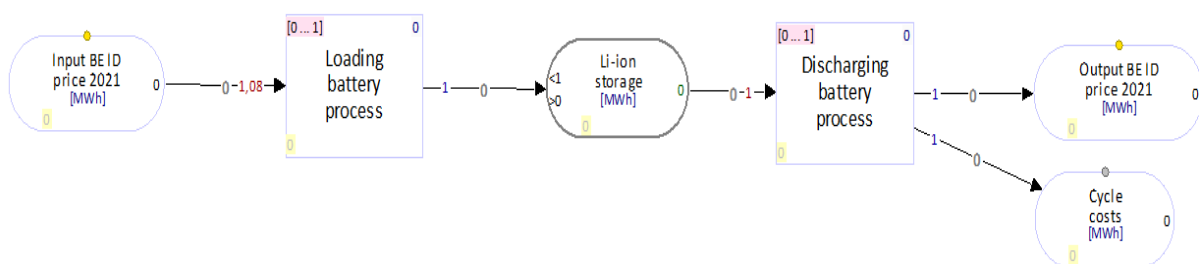


Figure 13. Linny-R model for calculating the intraday market income.

5.3.1.1 Roll and look-ahead period

As mentioned in 4.3.1.1, trades in the intraday market are done, on average, 5 minutes up to 8 hours ahead of the delivery moment. Even though you can look further ahead in practice (up to 33 hours), there has been chosen for a more conservative forecast, which the look-ahead period is constrained to 8 hours in this research and the roll period is 1 hour. Basing revenue forecasts on historical prices implies perfect foresight under the assumption of knowledge on the realized prices and, which will further be discussed in 8.2.2.2.

5.4 FCR income modelling

The remuneration of electric time-shifting in the intraday market is per energy unit (€/MWh). In contrast, FCR providers receive remuneration for the reservation of power capacity (€/MW). The results of the current FCR symmetrical 200 mHz product in the common auction on Regelleistung between 1 July 1, 2019, and September 29, 2019, are shown in Figure 14. It shows the Belgium marginal capacity price, which represents the price of the last bid to meet the capacity demand. Every awarded Belgium capacity provider receives the same remuneration from Elia (ENTSO-E, 2018b).

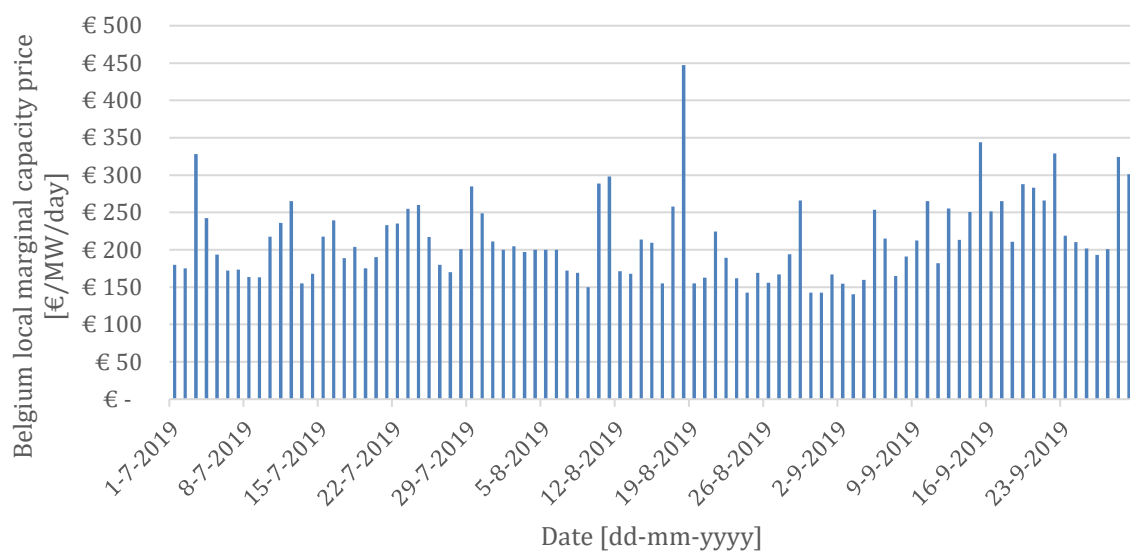


Figure 14. Marginal capacity price in Belgium on the regional platform between July 1, 2019 – September 29, 2019 (Regelleistung, n.d. -b).

The results shown in Figure 14 has let to the conclusion that no clear trend upwards or downwards can be identified. The average price during the period was € 213,55/MW/day, the minimum price € 140,33/MW/day, and the maximum price € 447,34/MW/day. Thus, if the BESS wanted to be awarded in all auctions between July 1, 2019, and September 29, 2019, it should have bid at least € 140,33/MW/day every auction based on pay-as-clear design.

Figure 15 shows the frequency of the continent Europe synchronous area on any day in 2018, the nominal 50 mHz frequency line, - 10 mHz line and the + 10 mHz line. The surface between - 10 mHz and + 10 mHz indicates the dead band, which means no FCR regulation is allowed if the frequency is in this area. Action by FCR suppliers is mandatory if the frequency exceeds the - 10 mHz or + 10 mHz. (Elia, 2019b).

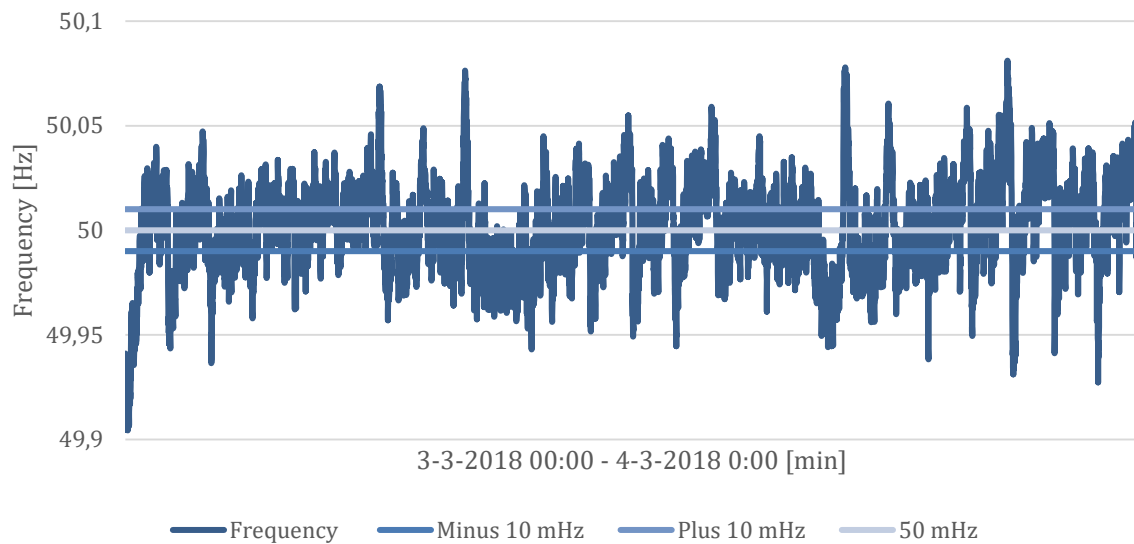


Figure 15. Continental Europe synchronous area frequency 3-3-2018 00:00 - 4-3-2018 00:00 (RTE, 2019).

The BESS discharges and charges by supplying and absorbing electricity from the grid. The calculation of the number of cycles per year is based on the network frequency of 2018, FCR requirements and the BESS power capacity (RTE, 2019). As mentioned in 5.1.2.1.2, the minimum dimensioning of the BESS for the FCR is 10 MW/6,7 MWh according to the FCR requirements. BES should always have sufficient energy capacity to be fully activated for at least 15 minutes during a frequency alert state. Therefore, a power and energy band, upwards and downwards, 2,5 MWh is reserved (Elia, 2019b). Thus, the minimum state of charge of the battery is 2,5 MWh and the maximum state of charge is 4,2 MWh. Given the constraints above, the BES would have made, rounded up, 362 cycles upwards and 362 cycles downwards, which is 362 full cycles per year in 2018. 362 cycles per year will be the initial situation in this research for FCR deployment with 10 MW/6,7 MWh. Details on the calculations can be found in appendix 12.3.1.

5.4.1 Charging costs

Moments have been identified in which the BESS is exhausted but should have delivered energy because of its obligation to the FCR. Based on the frequency data and the constraints above, 34 MWh should have been bought in the electricity market for these moments. The yearly charging costs from 2021-2030 are derived by multiplying the particular forecasted day-ahead market price times the 34 MWh required per year. The charging costs will be subtracted from the FCR income.

5.5 CRM contract length

In 4.1.1.8, the combinations of delivery periods and investment thresholds of different European CRMs have been introduced and are shown again in Table 16. As mentioned in 4.1.2.5, capacity suppliers might, depending on the investment threshold, be eligible for CRM contracts with a maximum of 1, 3, 8 or 15 years. This study assumes that the BESS lifetime is (at least) as long as the duration of the capacity contract. In the end, the capacity provider is obligated to deliver the contracted capacity throughout the entire contract period.

CRM	Delivery periods [years]	Investment threshold [€/MW]
United Kingdom	1	n/a
	3 (T-4 auction 2021/22)	152.550
	15 (T-4 auction 2021/22)	305.100
Irish all-island	1	n/a
	Max. 10	300.000
Poland	1	n/a
	5 (7 If CO ₂ < 450kg/MWh)	117.647
	15 (17 If CO ₂ < 450kg/MWh)	705.882
Italy	1	n/a
	15	186.000

Table 16. Investment levels of European CRMs (CREG, 2019).

The CAPEX of BES (1-hour storage depth) in this research in 2025 and 2030 are respectively € 312/MW and € 224/MW (IRENA, 2017). Given the investment thresholds, a BESS built-in 2025, i.e., the CAPEX of € 312/MW would obtain the longest contract in the United Kingdom, Irish all-island and Italian CRM. Therefore, the expectation is that BES is eligible for at least an 8-year CRM contract. This means that the BES capacity provider could also choose for a CRM contract of less than 8 years.

As mentioned in 5.3.1, BES generate income by purchasing (charging) energy at low prices and selling (discharging) at high prices. By way of illustration, Figure 16 shows forecasted intraday market income in 2026 for a different number of cycles. In line with expectation, the intraday market income decreases as the number of charge-discharge cycles decreases. Therefore, it seems beneficial to make as many cycles per year as possible.

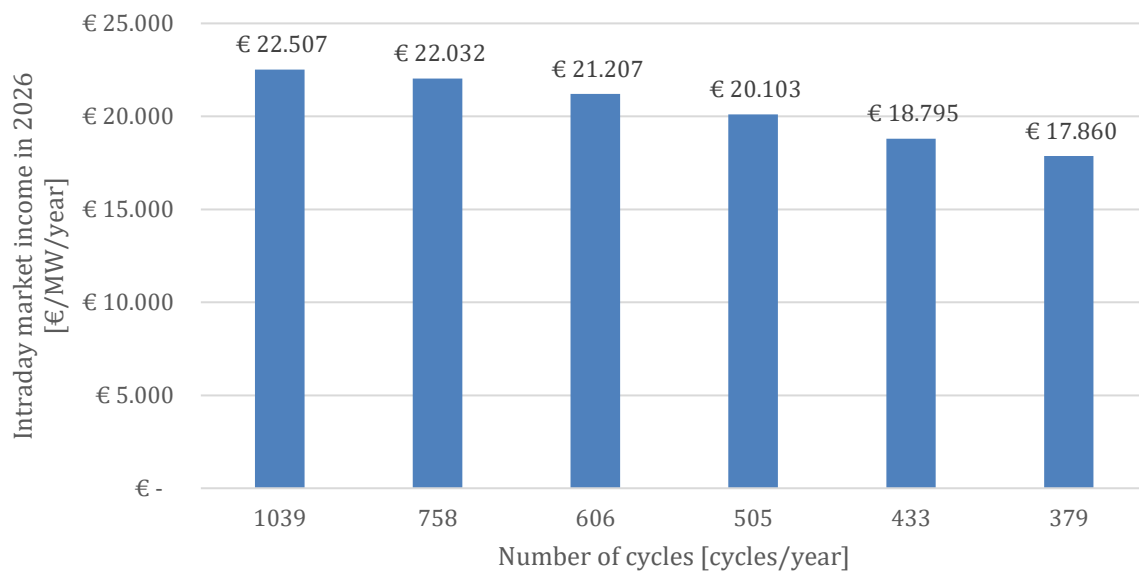


Figure 16. Intraday market income (2026) by operating different number of cycles.

However, BES lifetime is affected by charge-discharge cycles and the lifetime is often expressed in the (maximum) number of full equivalent cycles (Dufo-López, Lujano-Rojas, & Bernal-Agustín, 2014). The BES lifetime (in years) may be longer by limiting the number of cycles per year, compared to the situation where no restrictions are imposed on the maximum number of cycles per year.

Figure 17 shows the aggregated intraday market income over BES lifetime in years and the corresponding maximum number of cycles per year. This research assumes 3031 equivalent cycles for Li-ion BESS in 2025 as mentioned in 5.2.1. As an example, the first stacked bar chart of Figure 17 shows the intraday market income over three years (2026, 2027, and 2028) where the number of cycles per year is not limited by calculating the income in Linny-R. Initially, Linny-R sets no restrictions to the number of charges and discharges, i.e., the number of cycles, for solving the linear optimisation problem. The 3-year lifetime follows from dividing the BES lifetime of 3031 cycles by the 1039 cycles. Subsequently, the maximum cycles per year and the corresponding income has been calculated for a lifetime of 4, 5, 6, 7 and 8 years.

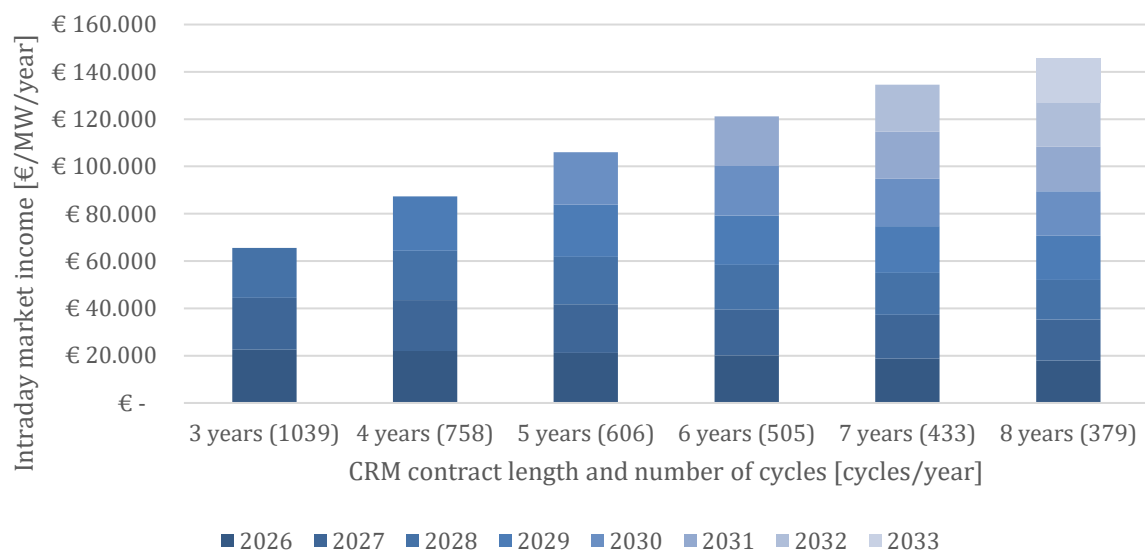


Figure 17. Aggregated intraday market income for different BES lifetime (years).

Figure 17 shows that limiting the number of cycles per year ultimately leads to a higher income over the entire BES lifetime. The additional income from performing more cycles do not outweigh the income that you can earn in more years by limiting the number of cycles per year. Therefore, it is desirable to opt for an 8-year CRM contract since this results in a lower required capacity remuneration compared to a shorter contract.

5.6 Scenarios

5.6.1 CRM design scenarios

Two scenarios have been drawn up due to the uncertainty regarding definitive market CRM market design. The reference scenario can be described as a conservative scenario. It assumes the relatively low strike proposed in Italy (€ 125/MWh), which is expected to lead to a higher payback obligation compared to the situation with the Irish all-island strike price. Furthermore, it is based on the last and also the smallest, least favourable, de-rating factor of the considered European CRMs (29,4% for 1-hour storage depth). The optimistic scenario assumes the most favourable strike price (€ 500/MWh) and de-rating factor (39,4% for 1-hour depth of storage) that occurs in the considered European CRMs. As mentioned in 7.3.2, the payback obligation is equal to zero with a strike price of € 500/MWh. This means, there is no payback obligation in the optimistic price scenario, which leads to zero costs associated with participating in the CRM.

Parameter	Reference scenario	Optimistic scenario
Strike price	€ 125/MWh	€ 500/MWh
De-rating factor (1-hour storage depth)	29,4%	39,4%

Table 17. Reference scenario and experiments for calculating the required capacity remuneration.

5.6.2 Intraday market price scenarios

Table 18 shows the average day-ahead market price of 2018 and Elia's predictions for 2020, 2023, 2025, 2028 and 2030 based on Figure 9 and the assumptions in 4.4.1 (Eneco, personal information, June 26, 2019; Elia, 2019d). The last column shows the percentage change of the day-ahead market price between the subsequent years. This percentage change is also assumed for the intraday market price for forecasting the prices in 2020, 2023, 2025, 2028 and 2030. The hourly intraday market prices of the missing years between 2020-2030, i.e., 2019, 2021, 2022, 2024, 2026, 2027, 2029, are approximated through linear interpolation. For example, the price of 2019 is the average of the prices of 2018 and 2020. In practice, this price trend could also be non-linear. However, this is the best assumption available due to the limited data. Besides, the number of consecutive missing years is limited and the price differences between the consecutive years is relatively low, which is shown in appendix 12.2.1. Therefore, the impact of linear interpolation is assumed to be limited.

Price year [year]	Average day-ahead market Belgium [€/MWh]	Percentage change regarding the previous price [%]
2018	55,27	
2020	44	-20,4%
2023	50	+13,6%
2025	49	-2%
2028	45	-8,2%
2030	51	+13,3%

Table 18. Average day-ahead market price 2018 predictions for 2020, 2023, 2025, 2028, 2030 including percentage change.

5.6.2.1 Payback obligation

The market reference price is equal to the Belgium day-ahead market price as mentioned in 4.1.2. The Belgium day-ahead market price from 2020-2030 has been calculated based on Elia's flexibility study average day-ahead market price forecasts as discussed in the previous chapter (Elia, 2019d). The percentage price changes are used to calculate the hourly day-ahead market price in 2020, 2023, 2025, 2028 and 2030 with the price of 2018 as its base year. The hourly prices of the missing years from 2020-2030 are approximated through linear interpolation between the calculated years. The payback obligation is calculated for 2020-2030 for the Italian strike price of € 125/MWh and Irish all-island strike price of € 500/MWh.

As an example, Figure 18 shows the hourly Belgian day-ahead market price forecasts of 2025 with the strike price of € 125/MWh.

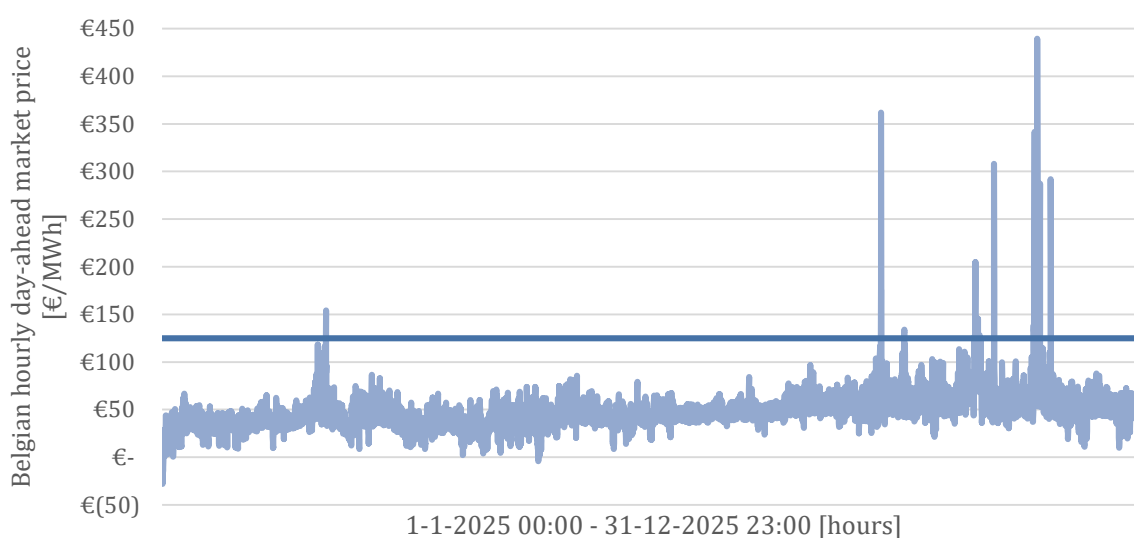


Figure 18. Payback obligation in 2025 with strike price € 125/MWh.

Table 19 shows the payback obligation from 2021-2030 with a strike price of € 125/MWh. The payback obligation from 2021-2030 is zero if the strike price is € 500/MWh since the maximum forecasted day-ahead market price is € 452/MWh.

Year	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Payback obligation [€/MW]	3380	3387	3509	3399	2246	3474	3308	3342	3387	3392

Table 19. Payback obligation with strike price € 125/MWh (2021-2030).

5.6.3 FCR price scenarios

This research assumes that the FCR price is not expected to rise in the future and are more likely to fall as discussed in 4.4.2. The following three price scenarios are taken into consideration:

1. The FCR price is the average price since the introduction of the regional FCR auction on July 1, 2019, till September 30, 2019: € 215,83/MW/day;
2. The FCR price is the lowest price since the introduction of the regional FCR auction on July 1, 2019, till September 30, 2019: € 140,33/MW/day;
3. The FCR price is 50% of the (average) FCR price in the first price scenario: € 106,78/MW/day;

The first two price scenarios reflect the prices observed today and the third scenario shows the price in an extreme case.

5.7 Experiment design

This section discusses the experiment design of modelling the required capacity remuneration for BESS. BESS is assumed to operate in the intraday market, FCR market or in both the intraday and FCR market. The experiments takes CRM design scenarios, intraday market scenarios and FCR scenarios into consideration as discussed in 5.6 and the corresponding expected storage costs from 5.4.1. The required capacity remuneration will be modelled for the photo years 2020, 2025 and 2030. The years are briefly described in the table below. The BESS will be built in 2020, 2025 and 2030 and are in operation from respectively 2021, 2026 and 2030 till the end of the BESS its lifetime. The BESS lifetime is equal to the CRM contract of 8 years as mentioned in 5.5.

Year	Description
2020	Competitiveness of BES in today's energy market with (theoretically) a CRM
2025	Competitiveness of BES in the first CRM auction
2030	Competitiveness of BES in the 6 th (T-4/T-1) CRM auction

Table 20. Year description of scenarios 2020, 2025 and 2030.

Table 21 shows the experiments for a BESS (10 MW/10 MWh) operating in the intraday market. The price scenario *Elia DA* is the price scenario as discussed in 5.6.2 which is based on Belgian wholesale market forecasts from Elia. *Reference* and *optimistic* refer to the CRM design scenarios introduced in 5.6.1.

Year	CRM design scenario	Price scenario
2020	Reference	Elia DA
	Optimistic	Elia DA
2025	Reference	Elia DA
	Optimistic	Elia DA
2030	Reference	Elia DA
	Optimistic	Elia DA

Table 21. Experiments for BESS (10 MW/10 MWh) operating in the intraday market.

Table 22 shows the experiments for a BESS (12,5 MW/10 MWh) operating in the FCR market. *Average, minimum* and *50%* refer to the FCR price scenarios as described in 5.6.3.

Year	CRM design scenario	Price scenario
2020	Reference	Average
	Optimistic	Average
	Reference	Minimum
	Optimistic	Minimum
	Reference	50%
	Optimistic	50%
2025	Reference	Average
	Optimistic	Average
	Reference	Minimum
	Optimistic	Minimum
	Reference	50%
	Optimistic	50%
2030	Reference	Average
	Optimistic	Average
	Reference	Minimum
	Optimistic	Minimum
	Reference	50%
	Optimistic	50%

Table 22. Experiments for BESS (12,5 MW/10 MWh) operating in the FCR market.

Table 23 shows the experiments for a BESS (12,5 MW/10 MWh) operating in both the intraday and FCR market. As explained in 5.2.1.2, 6,7 MWh of the total 10 MWh BESS energy capacity is reserved for the FCR operation and 3,3 MWh is used for energy time-shifting in the intraday market.

Year	CRM design scenario	Price scenario
2025	Reference	Minimum
	Optimistic	Minimum

Table 23. Experiments for BESS (12,5 MW/10 MWh) operating in both the intraday and FCR market.

6 Verification and validation

6.1 Verification

The Linny-R model for calculating the intraday market income will be verified to evaluate if the model performs as it is intended to. Model verification concerns with building the model right (Balci, 1994). The Linny-R model should find the optimal moments for buying and selling electricity to maximise profit. Figure 19 shows the behaviour of the Linny-R model for the year 2026 during the first 28 time steps, i.e., hours.

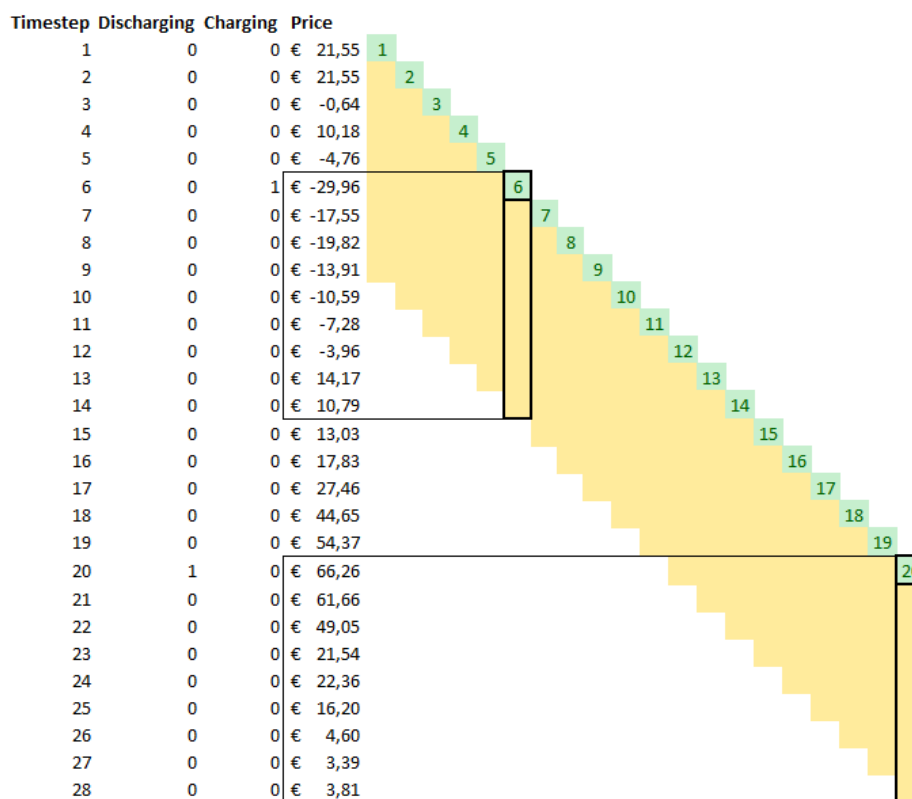


Figure 19. Verification of Linny-R model of 2026.

The number one indicates whether an operation is active in its specific hour. The second column represents the activity of discharging and third column represents charging. The fourth column shows the day-ahead market price during its corresponding hour. As discussed in 5.3.1.1, the considered optimisation and look-ahead period in this research of receptively 1 hour and 8 hours are taken into account. The green blocks represent the optimisation period and the yellow blocks the look-ahead period. The numbers in the green blocks indicate the number of optimisation stages. The first operation is done by the BESS in hour 6.

The model then decides whether to charge and thus buy electricity for € -29,96/MWh, i.e., receiving instead of paying money because of the negative electricity price and looks ahead eight prices. € -29,96/MWh is the best price given the stage length.

Now that the BESS has been charged it seeks the best moment to sell the electricity while considering the roundtrip efficiency losses, which is found at hour 20. The price at hour 20 is the highest of the prices from hour 20 – hour 28. Thus, the Linny-R model simulates the behaviour that can be expected from energy time shifting. However, it should be kept in mind that the BESS could earn more income by charging and discharging more frequently. The BESS is constrained to 378 cycles per year due to the BESS cycle life and the 8-year CRM contract as explained in 5.5, which means the battery charges and recharges less often.

6.2 Input validation

The input validation considers whether storage costs estimated in this research correspond somewhat to the actuals storage costs of realized projects. The CAPEX of the BESS is based on IRENA's electricity storage costs outlook from 2017 (IRENA, 2017). According to Navigant Research, the price of 10/40MWh BESS is around \$15,8 million in 2019 which almost corresponds to IRENA's estimates (Eller, 2019). However, it is difficult to find out what the actual costs are as developers in press releases often present approximated project costs. The published (approximated) costs of projects in Lake Bonney (Australia), Cremzow (Germany) and Carboneras (Spain) plus the estimated storage costs in 2016 by IRENA (2017) are shown in Table 24

Location (start construction)	Power capacity [MW]	Energy capacity [MWh]	Total project costs [M€]	IRENA's estimated storage costs in 2016 [M€]
Lake Bonney (2018)	25	52	23,4	25,6
Cremzow (2018)	22	34,8	17	17,9
Carboneras (2017)	20	11,7	11,5	7,8

Table 24. Published (approximated) project costs by developers compared to IRENA's estimated storage costs (Infigen, 2018; Enel, 2019; Endesa, 2017; IRENA, 2017).

Assuming that the project quotations for projects starting construction in 2018 are made in 2017, the prices published by developers and IRENA seem to be quite similar in the first two examples. The prices of IRENA are somewhat higher since these were the prices for 2016. There is a greater difference between the published project costs and IRENA in the last example. This could be due to a too high estimate by the developer or a more expensive supplier of the battery packs. On the other hand, it is most likely due to a smaller power/energy capacity dimension of the BESS in the first two examples. The calculation method of IRENA determines the CAPEX based on power and energy capacity. However, the dimensioning of the power and energy capacity and the CAPEX is not an exact linear relationship. Economies of scale effects occur since greater dimensioning of the power and energy capacity leads to cost advantages. Therefore, the IRENA costs outlook might more accurate for greater BES dimensions and the costs of the considered 10 MW BESS is probably higher. IRENA's outlook is based on data of storage projects. If these projects were mainly larger projects, this makes sense. An accurate estimate of the storage costs can ultimately be obtained by requesting quotes from manufacturers

6.3 Model validation

Validation concerns with building the right model (Balci, 1994). Thus, whether the assumptions that have been made represent the real-world system with sufficient. The calculated intraday market income have been compared with realized results by Eneco's 48 MW BES system in Germany. The results seem to be somewhat similar, taking into account the power and energy capacity that has been deployed by Eneco in the intraday market in the best possible way (Eneco, personal information, October 17, 2019). However, the realized income is lower compared to the modelling results. The difference can largely be explained by the fact that in the Linny-R model, the maximum amount of energy that can be purchased or sold is equal to the BESS energy capacity, i.e., 10 MWh. In reality, this does not happen. Smaller volumes are bought and sold, which is less economically optimal compared to the optimization by Linny-R and leads to a lower income.

7. Results

In this chapter, the competitiveness of BESS in the intraday market and in the FCR market will be discussed according to the NPV and the required capacity remuneration for the years 2020, 2025 and 2030. The calculation is based on a CRM contract N of 8 years and a real rate of return r_r of 5,7% (based on the nominal rate return r_n 7% and inflation rate r_i 1,26%). The competitiveness has been assessed in the reference scenario and the optimistic scenario as presented in the experiment design.

7.2 Competitiveness in the intraday market

The NPV for both the reference scenario and the optimistic scenario has been calculated for the years 2020, 2025 and 2030 and are shown in Figure 20. The NPV is negative in all the situations, which means the projects will result in a net loss and the investment should be rejected. Thus, BES is not competitive in today's market nor in the future without any capacity remuneration. The decrease in NPV for the different years is mainly because of the strong storage costs reduction and to a lesser extent to the income increase. The CAPEX has been decreased by 48% between 2020-2030 while the intraday market income has increased only by 17%.

Figure 20 shows the required capacity remuneration in the reference scenario and the optimistic scenario for the years 2020, 2025 and 2030. The lower required capacity remuneration in the optimistic scenario is mainly because of the higher de-rating factor and because of the zero payback obligation. As mentioned in 2.3.1, the auction clearing price in Irish all-island and United Kingdom's capacity auctions with the presence of BES varied from € 6,80 – 46,15/kW/year in 2018 and 2019. This implies the BESS are built before the delivery years 2018 and 2019. Even with the significant storage costs reductions expected in 2020, 2025 and 2030, BES is most likely not competitive in the intraday market.

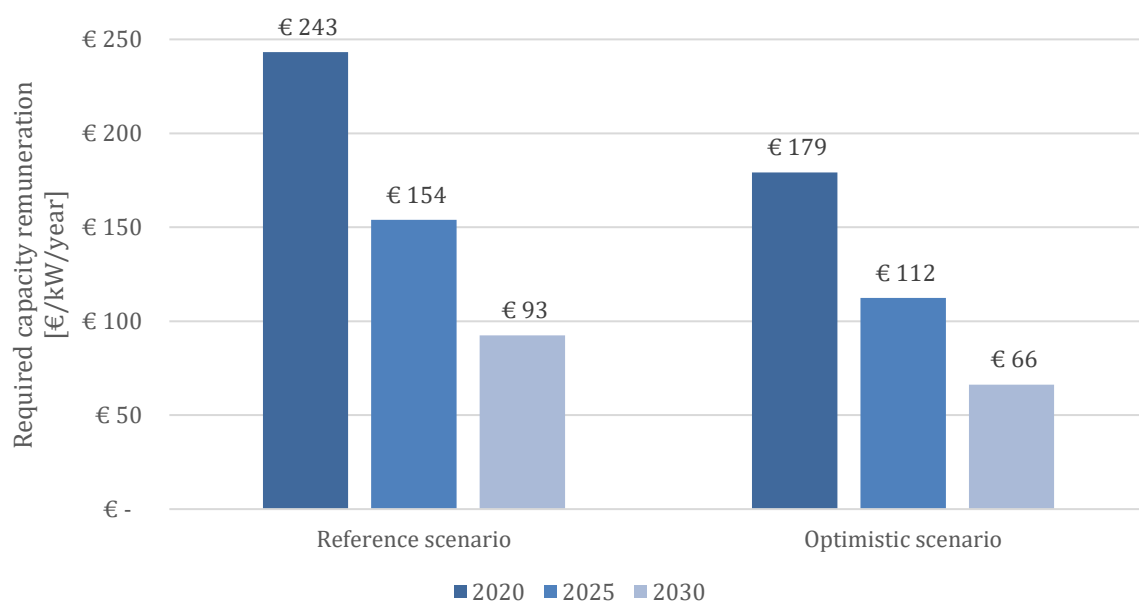


Figure 20. Required capacity remuneration, given the day-ahead market income in the reference scenario and in the optimistic scenario (2020, 2025, 2030).

7.2.1 Doubling the depth of storage

As mentioned in 4.1.2, energy-constrained capacity providers are awarded in the CRM according to their corresponding de-rating factor, which depends on the depth of storage. The greater the contribution towards adequacy, the greater the de-rating factor and thus the greater the capacity remuneration. Furthermore, a greater depth of storage could generate more income by capturing price spreads more effectively given the same amount of (charging and discharging) cycles. However, greater depth of storage entails additional CAPEX costs, more specifically energy capacity costs, and O&M costs. The question is whether the additional intraday market income capacity outweighs the additional storage costs.

The average intraday market income from 2026-2033 (2025 scenario) increases by 27% if the storage depth doubles. In this research, the 10 MW/10 MWh BESS will become a 10 MW/20 MWh BESS, which means the CAPEX energy installation costs increase because of the additional 10 MWh. The total CAPEX, consisting of the energy and power installation costs increases 75% with the 10 MW/20 MWh BESS compared to the 10 MW/10 MWh. The additional intraday market income does not outweigh the extra storage cost, thus doubling the storage depth leads to a larger negative NPV of the project. The required capacity remuneration increases from € 154 to € 163/kW/year. Therefore, more storage depth in 2025 will not increase the competitiveness of BES.

7.2.2 Conclusions

Figure 20 has shown the relatively high required capacity remuneration for the years 2020, 2025 and 2030 in the reference and the optimistic scenario. Given capacity remunerations below € 50/kW/year in other European CRMs, which includes prices near zero in the United Kingdom, it is unlikely that BESS is competitive if it operates in the Belgian intraday market.

Figure 21 shows the breakdown of the EBIDTA for 2020, 2025 and 2030 in the reference scenario. It includes the accumulated intraday market income and variable costs, i.e., O&M costs and the payback obligation during the 8-year CRM contract. The figure clearly shows the relatively high variable costs compared to the income, which has a major influence on the competitiveness of BESS.

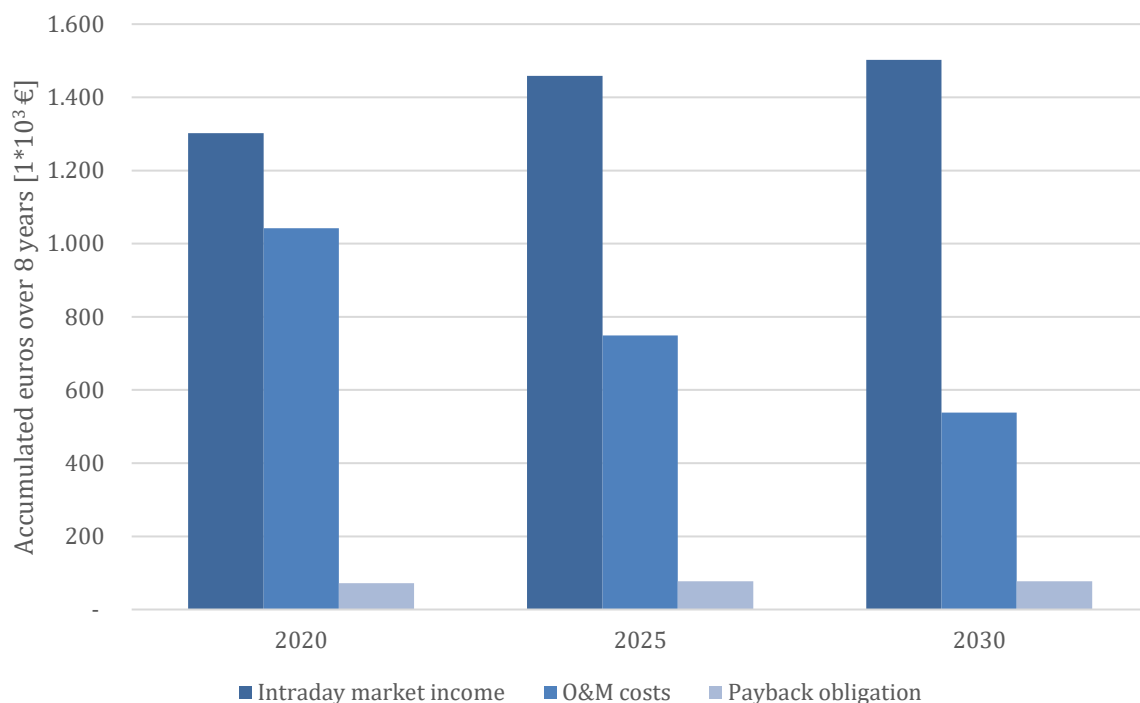


Figure 21. Breakdown of the EBIDTA for 2020, 2025 and 2030.

7.3 Competitiveness in the FCR market

The NPV and the required capacity remuneration will be discussed in this chapter per FCR price scenario. The price scenarios, as presented in 5.6.3, will again be briefly explained.

7.3.1 Average FCR price scenario

The price in the *average FCR price scenario* is the average capacity price between the introduction of the regional FCR auction on July 1, 2019 and September 30, 2019. The yearly remuneration is equal to the average FCR price of € 215,83/MW/day multiplies by 10 MW nominated power capacity in the FCR auctions, as assumed in the scenarios, times 365 days per year. Thus, the capacity provider will receive € 787.792/year in the average FCR price scenario during the 8-year CRM contract. The other two scenarios are also calculated in the same way.

Given the average FCR price, the NPV is negative in 2020, which means the investment result in a nett loss and should be rejected. The NPV in the optimistic scenario and both 2025 and 2030 scenarios are positive which implies no capacity remuneration is necessary. It can be derived from Figure 22 that BESS seems to be competitive in the FCR market in 2025 and 2030 given the average FCR price scenario. However, it is not very likely that the current average FCR price is equal to the average FCR price in 2025 and 2030 given increasing competitiveness in the FCR market due to replacement of baseload nuclear capacity by flexible generation capacity, as discussed in 5.4.3.

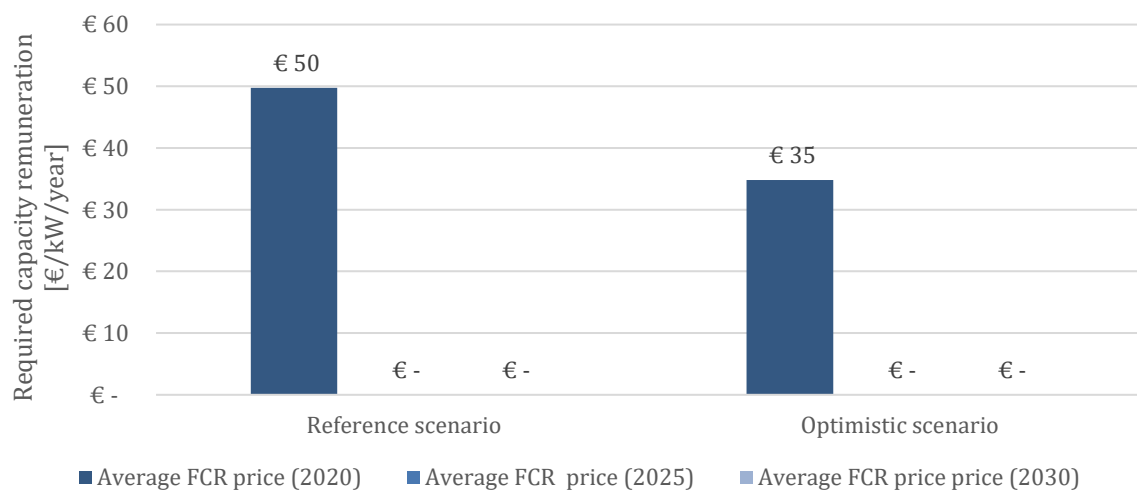


Figure 22. Required capacity remuneration, given the average FCR price in the reference and optimistic scenario (2020, 2025, 2030).

7.3.2 Minimum FCR price scenario

The price in the *minimum FCR price scenario* is the minimum capacity price between the introduction of the regional FCR auction on July 1, 2019 and September 30, 2019, which is € 140,33/MW/day. The FCR price, and thus the income, is 35% lower compared to the previous average FCR price scenario. The NPV of the project is negative for both scenarios in 2020, 2025 and 2030. However, the year 2025 is still more important than 2020 since the remuneration starts from November 2025.

Figure 23 shows the required capacity remuneration is limited in 2025 to € 55/kW/year in the reference scenario and € 39/kW/year in the optimistic scenario. In the previous price scenarios, the de-rating factor and a high strike price did not seem to have a decisive role. However, in this price scenario, the 11 euros that you need less in the 2025 optimistic scenario compared to the reference scenario may be decisive whether the business case of BES is competitive, given the capacity remunerations in recent European CRMs (€ 6,80 – 46,15/kW/year). BES might be competitive from 2025 if the FCR capacity price is equal to the lowest price observed in today's FCR market. However, the results are not convincing and too dependent on favourable parameters and capacity prices.

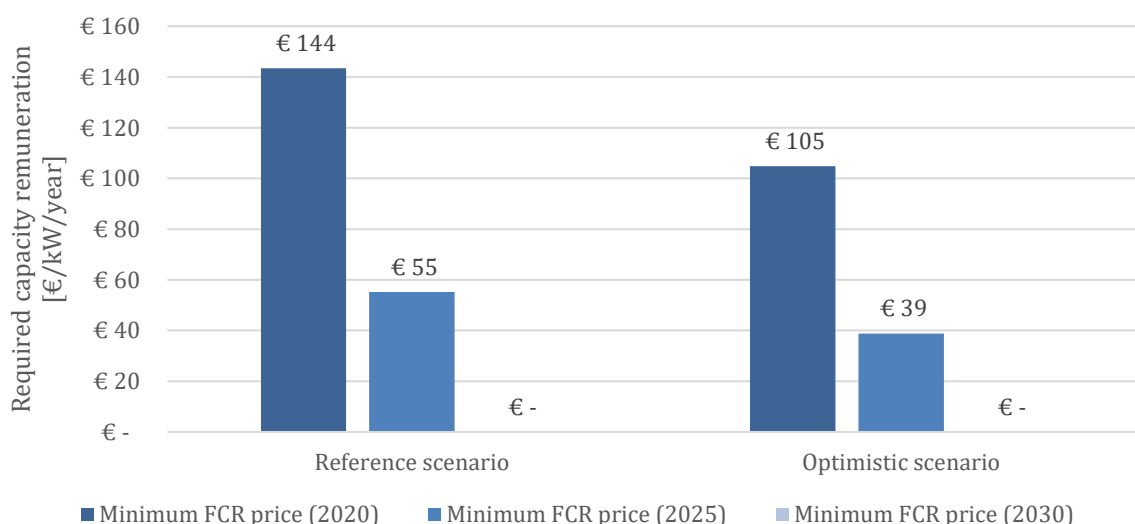


Figure 23. Required capacity remuneration, given the minimum FCR price in the reference and optimistic scenario (2020, 2025, 2030).

7.3.3 50% Average FCR price scenario

The price in the *50% average FCR price scenario* is 50% of the average capacity price between the introduction of the regional FCR auction on July 1, 2019 and September 30, 2019, which is € 106,78/MW/day. This means the FCR income decreased again by 24% compared to the previous scenario. Now the NPV of the project is negative in all situations and dependent on capacity remuneration as in Figure 24. BES is most likely not be competitive at all in 2025 because of the high required capacity remuneration. The required capacity remuneration in 2030 looks favourable, but it is uncertain how the FCR prices will develop over time. The FCR market may already be saturated by that time and the capacity remuneration is already heading towards zero, as seen in the United Kingdom CRM auction.

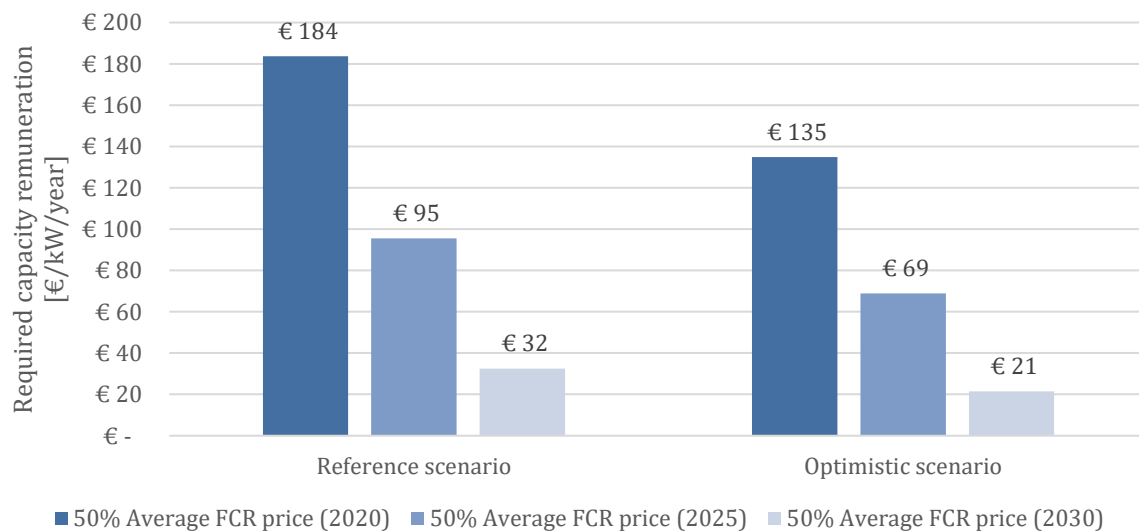


Figure 24. Required capacity remuneration given 50% of the average FCR price in the reference and optimistic scenario (2020, 2025, 2030).

7.3.4 Revenue stacking of FCR and intraday market income

In this research, the BESS dimensioning operating in the FCR market is 12,5 MW/10 MWh as mentioned in 5.2.1.2. However, only 6,7 MWh of the 10 MWh is continuously reserved for FCR provision in this research. The unused energy capacity of 3,3 MWh is reserve capacity for charging and discharging moments and can be used most of the time for energy time-shifting in the intraday market. No extra power capacity is required for energy time-shifting while being active in the FCR auction. The additional 25% power capacity of 2,5 MW is only used during moments when charging or discharging is required in the FCR market. Thus, the BESS dimensioning will be same when operating in the FCR and intraday market. Figure 25 shows the required capacity remuneration if the BESS operates only in the FCR market versus operating in both the FCR market and the intraday market. The required capacity remuneration decrease by 36% because of the additional income from the intraday market. Therefore, revenue stacking has a significant impact on competitiveness.

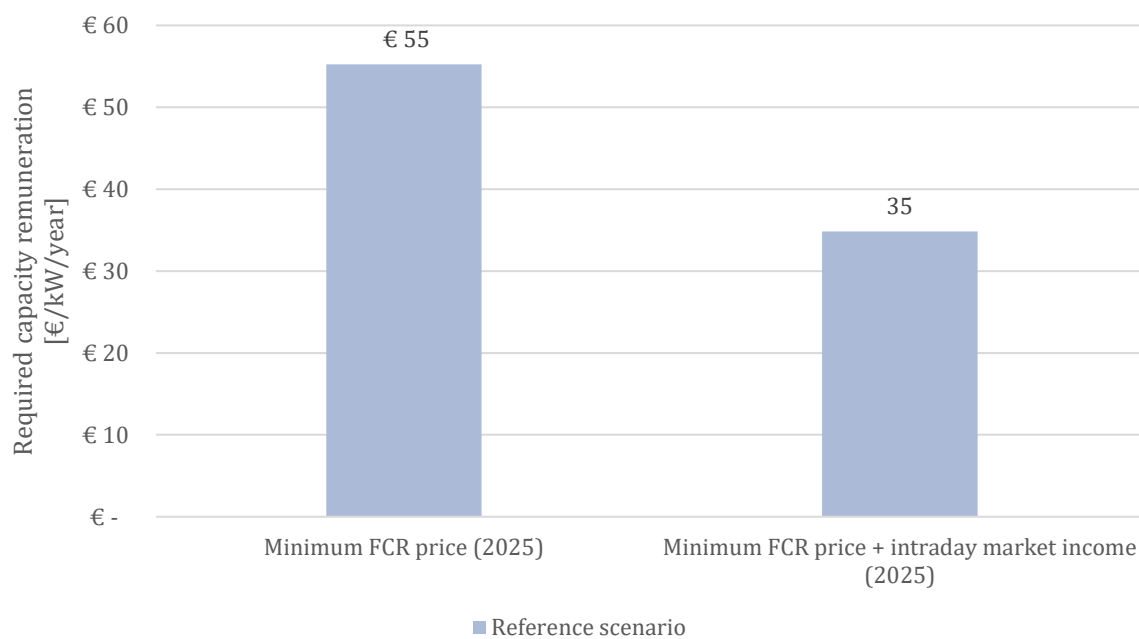


Figure 25. Combining intraday market and FCR incomes.

7.4 Conclusions

The future looks bright for BESS from 2025 and onwards, given today's average FCR price. However, if the average FCR price decrease 35% to the minimum FCR price measured today, BES is expected to be a lot less competitive. Halving the average price today would be disastrous. The stronger competitive position in the FCR market comes mainly from the higher FCR income compared to the intraday market income. The maximum yearly intraday market income is compared in Table 25. The FCR income is almost two times higher compared to the intraday income in every price scenario. This is also the main reason for the difference in competitiveness between operating in the two markets. Revenue stacking by combining the FCR and intraday market income would increase the competitiveness of BES and can be concluded to be necessary.

	Average intraday income [€/MW/year]	Average / minimum / 50% average FCR scenario [€/MW/year]
2020	16.123	78.779 / 51.221 / 39.390
2025	18.780	78.779 / 51.221 / 39.390
2030	20.376	78.779 / 51.221 / 39.390

Table 25. Income differences in the intraday market and the FCR market (2020, 2025, 2030).

8 Discussion

8.1 Results

8.1.1 Intraday market income

The intraday market income has been calculated based on the VWAP intraday market prices. The initial data intraday market data set of 2018 consists of 275.627 deals and the hourly VWAP price consists of 1-77 deals. The VWAP of a specific hour could include a great variety of deal prices, which is illustrated in Table 26.

Date	Volume [MWh]	Price [€/MWh]
01-01-2018 01:00	0,2	20
01-01-2018 01:00	0,2	30
01-01-2018 02:00	19,4	5
01-01-2018 02:00	0,1	2
01-01-2018 02:00	10	2
01-01-2018 02:00	15	-10

Table 26. Deals on the EPEX intraday market 1-1-2018 02:00.

Ideally, discharging, i.e., selling, would be favourable in the intraday market for the € 30/MWh and charging, i.e., buying, for the price of € -10 /MWh. However, there is no possibility in practice to capture these price spreads observed here. In practice, it is likely that there would already have been a purchase in the second hour for € 2/MWh because of the relatively low price. This means that there will no longer be bought for € -10/MWh. This also applies vice versa: the transaction of the energy capacity might have already occurred in the first hour for € 20/MWh instead of € 30/MWh. The VWAP on January 1, 2019, 01:00 is € 25/MWh, and 2:00 is € -0,74/MWh. Thus, Calculating the intraday market income based on the VWAP prices means that there is a loss in price volatility compared to reality where there is a possibility capturing this price volatility.

Besides, electricity market price volatility is expected to increase between 2030 – 2040 in Belgium because of the larger penetration of renewables, e.g., solar and wind energy, and relying more on demand-side response (DSR) to maintain adequacy (Elia, 2017b). However, the magnitude of the increase in price volatility is unclear. Therefore, the expected price volatility after 2030 has not been taken into account. Both reasons could underestimate the intraday market income. On the other hand, the optimization model in Linny-R calculates the optimal buy and sell moments assuming you know all the VWAPs which leads to perfect foresight, which will be further discussed in 8.2.2.2. To conclude, the intraday market income may be underestimated when using VWAP. However, considering the VWAPs compared to taken all the individuals deals into account leads to a more realistic approach.

8.1.2 Payback obligation

The payback obligation in this research depends strongly on the strike price of the reliability option in the CRM. A strike of € 125/MWh results in payback obligation from 2021-2038 while if the strike price is € 500/MWh, there is no payback obligation at all. This is due to the maximum forecasted day-ahead market price of € 452/MWh as mentioned in 5.6.2.1. Table 27 shows the influence of the payback obligation on the required capacity remuneration, given in the intraday market income and minimum FCR income in 2025. Assuming that the strike price would not drop below the € 125/MWh, the greatest influence of the payback obligation on the required capacity remuneration would be € 3/kW/year. A difference of € 3/kW/year may not have a decisive role in the investment decision in BES.

<i>In the reference scenario</i>	Required capacity remuneration [€/kW/year]	
	<i>With payback obligation</i>	<i>Without payback obligation</i>
Intraday market income (2025)	154	151
Minimum FCR income (2025)	55	52

Table 27. Influence of the payback obligation on the required capacity remuneration.

8.1.3 FCR income

As mentioned in 4.4.2, there are no clear forecasts on the FCR price development. However, the price is not expected to rise and more likely to fall in the future. The FCR prices are strongly demand-driven, and it is hard to model as stable income streams. Furthermore, the FCR income rests on the assumption that the BESS is awarded in every FCR auction. In practice, there might be moments that the FCR provider is not awarded in the auction because of relatively low bids of other participants or unforeseen circumstances.

8.2 Limitations

8.2.1 Data

All data used for the development of price scenarios in this study is publicly accessible and thus auditable. However, there are also research organisations, such as Bloomberg New Energy Finance (BNEF), which have also investigated electricity price developments and storage costs. These paid reports may not be published in this master thesis, so therefore there might be relevant data missing. Also, Eneco has electricity price forecasts that have not been included in the report due to competition sensitivity. Therefore, in a master thesis there is a limitation as to what is available to the public. By being allowed to use data from, for example, BNEF and Eneco, the reliability of the research can be increased. This could also be done by requesting quotes from storage costs. However, as mentioned in the validation, the storage costs estimates do not differ very great from the storage costs of realized projects.

8.2.2 Method

8.2.2.1 Net Present Value

The financial model for calculating the NPV of the project and after that, the required capacity remuneration, are performed in Excel. NPV is the most common technique for evaluating the profitability of a project. However, there are also drawbacks to this method. The calculation of the NPV is based on the required rate of return, which is chosen by the investors and often based on the risk of the investment, company's experience with similar projects, set by managers or a rule of thumb (Liljeblom, & Vaihekoski, 2004). The NPV can be unreliable if it is incorrectly selected due to inaccurate (risk) estimates. This research assumes a real rate of return r_r of 5,7% based on the nominal rate return r_n 7% and inflation rate r_i 1,26%. However, the nominal rate of return is a rough estimate. A risk profile can be drawn up based on this specific investment taking into account the likelihood of the related income and costs. This can lead to a better estimate of the required rate of return. The uncertainty about the future FCR and intraday market prices may lead to a higher nominal rate of return. A different real rate of return influences the NPV, the required capacity remuneration and thus the perception of the competitiveness of BES.

8.2.2.2 Linny-R

As mentioned in the model description, the intraday market income has been calculated with the use of a Linny-R model, which determines the optimal buy and sell moments over a certain period. The model assumes that there is knowledge into the intraday market prices a few hours in advance. This look-ahead period, which is assumed 8 hours in this research, reflects the time that, on average, traders look ahead when trading. However, the model looks ahead for 8 hours of realized intraday market prices, which causes perfect foresight.

The look-ahead period is halved to evaluate the influence of the look-ahead period on the intraday market income. This leads to the fact that the Linny-R model looks ahead 4 intraday market prices instead of 8 intraday market prices. The average intraday income decreases by 4% from 2026-2034 since the model buys and sells less optimally compared to the previous situation. The average intraday income from 2026-2034 has decreased by 4%. The required capacity remuneration in 2025 increases from € 154 to 156/kW/year with a look-ahead period of 4 hours instead of 8 hours. Therefore, the difference in the look-ahead period does not have a major impact on the competitiveness of BES.

8.2.3 Model and analysis

The NPV method can be seen as a common method for assessing the profitability of BES in electricity markets based on the number of studies found in literature (Oudalov, Chartouni, & Ohler, 2007; Cho, & Kleit, 2015; Mercier, Cherkaoui, & Oudalov, 2009). Striking is that none of these studies takes corporate tax rate into consideration when calculating the NPV. The Belgian corporate tax rate is 25% in 2020 as mentioned in 5.2.1 and has a significant impact on the NPV. By way of illustration, the required capacity remuneration in 2025 (reference scenario) decrease by 8% for a BESS operating in the intraday market if the corporate tax is not taken into consideration. Therefore, a disadvantage of the NPV method is that only projects can be compared with each other where the same assumptions have been made.

8.3 De-rating factor methodology

This chapter reflects on methodologies for determining de-rating factors of BES in the Belgian CRM. First, Elia's methodology for determining the de-rating factors of the Belgian CRM will be described. Subsequently, three operation strategies of BES will be discussed. Lastly, the methodology in the United Kingdom will be discussed.

8.3.1 Belgian methodology

An overview of the process for determining the de-rating factors of the Belgian CRM is shown in Figure 26. The different steps are explained below.

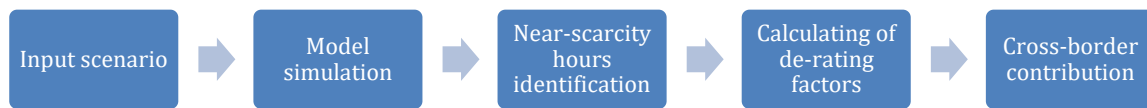


Figure 26. Process overview of the methodology for determining the de-rating factors of the Belgian CRM (based on Elia, 2019e).

The first step involves selecting the input scenario that is used to calculate the de-rating factors. Consumption growth and hourly consumption profiles, weather profiles, energy limitations and technology specifications, renewable energy capacity, thermal capacity, storage capacity, market response capacity and cross-border capacity between market zones are taken into consideration in the input scenario (Elia, 2019e).

Based on the input scenario, the statistical method Monte Carlo simulation is used to solve the unit commitment problem, which refers to scheduling the generation units to meet the generation demand while minimizing the operation costs (Valenzuela, & Mazumdar, 2001). The main variables of interest are the hourly generated energy per technology and the hourly exchange (i.e., import and exports) between market zones and these will be derived from the model output. Virtual generation capacity of 100% uptime is added to the system if the input scenario does not meet the Belgian adequacy criteria of 3 hours Loss of Load Expectation (LoLE)⁵ in the simulation (or removed in case of surplus capacity) (Elia, 2019e).

⁵ “Represents the number of hours per annum in which, over the long-term, it is statistically expected that supply will not meet demand” (DECC, 2013, p. 3).

Subsequently, the relevant hours for the adequacy in Belgium, i.e., near-scarcity hours, are determined based on the model output. Near-scarcity hours refers to both hours with energy not served (i.e., scarcity hours) and hours in which any additional domestic load will lead to Expected Energy Not Served (EENS). Domestic capacity and import capacity from Belgian's directly connected market zones, i.e., the Netherlands, United Kingdom, Germany, and France, are taken into account (Elia, 2019e).

The contribution of thermal generation units, e.g., CHP, OCGT and CCGT plants, to the Belgian adequacy is independent of weather conditions, activation limits and energy limitations. Only annual forced outage rates and the corresponding duration derived from historical input (scenario) data are taken into account for calculating the de-rating factors of these technologies. The de-rating factor of thermal technologies (%) is equal to 100% minus the specific assumed forced-outage rate (%) of the thermal technology (Elia, 2019e).

In comparison with the thermal technologies, the de-rating factors of energy-constrained technologies cannot be derived from historical data. The energy-constrained de-rating factors are calculated based on their contribution during near-scarcity hours, where the contribution is derived from the model output of a Monte Carlo simulation including all technologies. The model optimizes the costs of energy-constrained technologies so that the income from discharge is higher than the costs of discharge, which leads to a maximum contribution during near-scarcity hours. The de-rating factor of energy-constrained technologies (%) is its average contribution during near-scarcity hours (MW) divided by its reference power (MW) (Elia, 2019e).

As mentioned earlier in 4.1.1.2, SLA categories are defined, which consists of energy-constrained technologies with the same hourly activation constraints and assumed to be activated once a day. Each SLA category is associated with a specific de-rating factor and represents the contribution of the category to the adequacy. Elia will publish the de-rating factors in their yearly auction report (Elia, 2019e).

In the last step, the cross-border contribution has been calculated based on the model output. The average contribution of the directly connected market zones to adequacy is determined by maximum capacity contribution, i.e., capability, of the directly connected market zones to export during near-scarcity hours (Elia, 2019e). Belgium relies strongly on cross-border capacity to ensure its necessary level of adequacy. Furthermore, scarcity moments in Belgium are strongly correlated to scarcity moments in one of the directly connected market zones and is likely to increase in the future (Elia, 2019d).

8.3.2 BES operation strategies

European countries with a capacity mechanism are obligated to have reliability standards which indicate their security of supply requirement. The country's adequacy indicators include at least the LoLE and the EENS (European Parliament and of the Council, 2019). Both indicators are also taken into consideration in the Belgian CRM law and Elia's latest adequacy study (Belgische Kamer van volksvertegenwoordigers, 2019a; Elia, 2019d).

EENS provides a better indication of the fiscal damage of shortage periods, while the LoLE does not reflect on the severity of the shortage period. LoLE indicates only the period, i.e., hours, with the presence of EENS. One is indifferent which adequacy parameter is used if the electricity in the market is only supplied by solely dispatchable generators. This is because there is a direct relationship between the EENS and LoLE values since the varying level of capacity in the electricity market. However, there is no direct relationship anymore between EENS and LoLE for energy-constrained technologies, e.g., BES. BES has a (maximum) energy stored, so the reduction in EENS is more or less the same. BES can respond in different ways to EENS periods where each difference can lead to a different impact on the reduction in LoLE (Dent, Wilson, & Zachary, 2017).

Figure 27 presents three alternatives of the contribution of BES to reduce shortages. The dotted line with a parabolic shape represents the severity of the shortage, and the shortage occurs if the dotted line exceeds the x-axis. The area between the x-axis, the red line and the dotted line represents the energy provided by BES. The energy provided by BES and thus the reduced EENS. The red arrows indicate the Loss of Load (LoL) duration (Dent, Wilson, & Zachary, 2017).

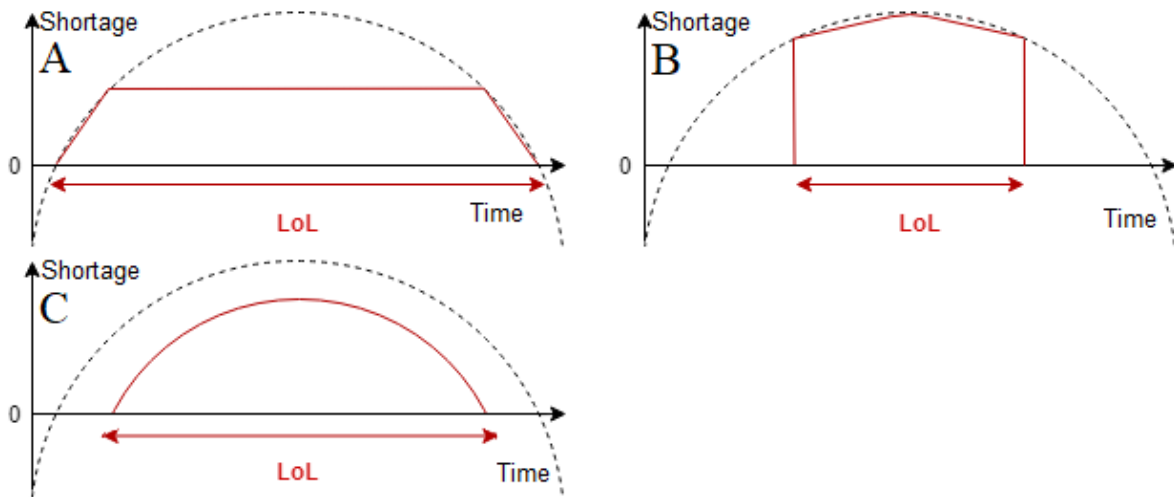


Figure 27. Alternative contributions of BES to shortage periods (Based on Dent, Wilson Zachary, 2017).

- In alternative A, the LoL is not reduced during the shortage period. However, BES brings down the maximum energy not served peak. The indicator LoLE actually underestimates the contribution of BES in this case (Dent, Wilson, & Zachary, 2017).
- In alternative B, the LoL duration is minimized by deploying BES during moments when the EENS is minimal. The BESS only contribute to periods where it can totally reduce the energy not served. However, reliable, inexhaustible capacity (i.e., firm capacity) which would achieve the same LoL reduction as BES in this example would supply energy during the entire shortage period. Thus, firm capacity would limit the energy not served more than BES. Now, the LoLE overestimates the contribution of BES (Dent, Wilson, & Zachary, 2017).
- In alternative C, BES delivers energy at a steady rate during the shortage period. The same reduction of LoL and EENS would be achieved by firm capacity. The LoLE values BES and firm capacity in the same way (Dent, Wilson, & Zachary, 2017).

As shown in Figure 27, the three alternatives for the deployment of BES lead to different reduction of the LoL duration given an equal availability of storage. Therefore, the most appropriate adequacy indicator for the contribution of BES is EENS because it is not sensitive to the strategy of BES deployment during shortage periods and represents the economic damages directly (Dent, Wilson, & Zachary, 2017; National Grid, 2017). The deployment of BES on the electricity market, e.g., timing and energy delivery profile, is a commercial decision. Therefore it is difficult to determine which strategy the storage operator will choose during shortage periods (National Grid, 2017).

Note that the presence of storage is still limited in the Belgian electricity market. Therefore, the available EES does not significantly affect the direct relationship between LoLE and EENS, as discussed earlier. Thus, the LoLE is still appropriate for determining the required capacity, i.e., level of security to be achieved by the Belgian CRM (Dent, Wilson, & Zachary, 2017; Elia, 2019e).

8.3.3 UK methodology

The required capacity, i.e., level of security to be achieved by the Belgian CRM, is calculated according to the LoLE adequacy criteria (Belgische Kamer van volksvertegenwoordigers, 2019a). Besides, the input scenarios in the Belgian de-rating methodology also relies on the same LoLE as mentioned in 8.3.2.1.

However, it is more appropriate to calculate the contribution of BES according to the EENS adequacy criteria, as explained in the previous subsection. The de-rating methodology for energy-constrained capacity providers used in the United Kingdom is actually based on the EENS metric (National Grid, 2017). Research by National Grid (2017) has shown that using the LoLE or EENS metric for calculating the contribution of storage is significantly different. Given BES is deployed as described in alternative C and taken into account that the input scenario is the same, the de-rating factor would be 29,9% (1-hour storage depth) if the methodology is based on the EEU, while the de-rating factor is 47,0% if the methodology is based on the LoLE (National Grid, 2017).

Besides, National Grid (2017) showed that the de-rating factor for a certain storage depth will decrease as the corresponding penetration of energy-constrained storage increases since the contribution to the security of supply decreases. Energy-constrained storage will cause an increase in the LoL duration, which means the contribution of that specific energy-constrained storage will saturate, and thus the de-rating factor will decrease (National Grid, 2017).

8.3.4 Conclusions

It can be concluded from previous subsections that calculating the contribution of BES based on the adequacy indicator EENS is most appropriate. In the Belgian methodology, the contribution of storage is based on the LoLE, which is beneficial for storage operators in terms of the de-rating factor as illustrated in the results above. The methodology may be adjusted as storage will play a dominant role in the Belgian energy supply. After all, this has also happened in the UK. Second, the de-rating factors are expected to decrease as the penetration of storage increases. In the light of both findings, it is therefore favourable for BES to participate in (one of the) first capacity auctions where the de-rating value may still be favourable for energy-constrained technologies.

9 Conclusions

This section includes the conclusion of the research on the competitiveness of BES in the future Belgian market. First, the sub-questions of this research, as introduced in 3.1, will be answered. Finally, the main research question will be answered. Hereafter, recommendations for further research will be presented.

9.1 Answers to the sub-questions

What are the characteristics of the Belgian Capacity Remuneration Mechanism?

The capacity remuneration mechanism proposed in Belgium is the (market-wide) central buyer capacity mechanism based on reliability options. The Belgian CRM market rules and auction rules are not known yet, and thus a selection has been made of the most likely characteristics, based on interim publications by parties involved and other CRMs in European countries. The market reference price, strike price and de-rating factors have been identified as the most important parameters for required capacity remuneration. The further elaboration of the mechanism on these parameters is therefore important for the competitiveness of BES.

Which EES technologies fit the characteristics of the Belgian capacity market best?

Various studies support that Li-ion battery storage is the best alternative for operating in the Belgian CRM. The technology is characterized by relatively low CAPEX, it still undergoes a major cost reduction, has a fast response time and meets the ancillary services requirements, and projects are relatively easy to realise. Therefore, Li-ion storage is abundant on ancillary services markets and common in other European CRMs.

What is the revenue derived from the wholesale electricity market and the potential payback obligation of the capacity remuneration mechanism?

The intraday market is preferred over the day-ahead market for BES due to the greater price volatility. The price volatility is likely to increase in the future due to the large share of renewables and relying more on DSR to maintain the adequacy in Belgium. This development offers opportunities for BES in the future since it may lead to potentially higher income. However, no studies have been found on the price development of the Belgian intraday market.

Capacity providers in the Belgian CRM auction are obligated to pay the difference between the market reference price, i.e., Belgian day-ahead market price, and a certain strike price whenever the day-head market price exceeds the strike price. No Belgian strike price has been mentioned during CRM meetings. The lowest strike price proposed in Europe is € 125/MWh. This strike price would only leads to € 3/kW/year difference in required capacity remuneration compared to a CRM without strike price. Therefore, the payback obligation is not expected to have a significant impact on the investment decision in BES.

What is the revenue derived from ancillary services?

BES would not require any capacity remuneration from the first capacity delivery year if the FCR price is equal to today's average FCR price. However, the research assumes that the FCR price is not expected to rise in the future and more likely to fall because of the increase of flexible generation capacity and the further integration of European ancillary service markets. The FCR price is likely to decline when the new ancillary service products will be implemented in July 2020. It is advisable to follow the FCR price development after this introduction. There is a lot of uncertainty about the future FCR prices and therefore the prices of the FCR scenarios vary widely (215,83 – 140,33 – 106,78 €/MW/day). Still, the FCR price will have to fall significantly to reach a comparable level of the intraday market price. Even if 3,3 MWh of the BESS energy capacity is actually unused, as explained in 5.2.1, the FCR market is still preferred over the intraday market.

What is the remuneration required for EES in Belgian capacity remuneration mechanism auction?

It is likely that the Belgian auction clearing price could drop to near-zero based on the auction results of other European CRMs. In this case, BES must be able to compete with probably (existing) gas plants. BES solely operating in the intraday market would not be competitive in the Belgian CRM auctions given the required capacity remuneration of at least € 66/kW/year in 2030. BES does not need capacity remuneration from 2025 onwards with today's average FCR price. This is due to the expected fall in battery prices up to 2025. However, it is not very likely that the capacity prices stays the same. The competitiveness of BES can, however, be improved by trading in the intraday market alongside FCR. Because of the minimum one-hour storage depth requirement in the Belgian CRM, part of the energy capacity is not used in the FCR and can be used for intraday market trading. The required capacity remuneration decreases significantly from 55 to 35 €/kW/year.

This research has shown that both uncertainties about price developments and auction design have a major impact on the required capacity remuneration. On the other hand, the uncertainties surrounding the auction design can soon be mitigated if the design is established by law.

9.2 Answer to the main research question

What is the competitiveness of electrical energy storage in the future Belgian capacity market?

The research has been able to determine which factors are related to the competitiveness of BES, such as the battery's cycling life, storage costs, reference price, strike price and the de-rating factors. However, uncertainties have been discovered regarding legislation, rules and prices. Part of this uncertainty will be eliminated when the CRM rules and auction parameters will be published. Deploying BES on electricity markets is expected to become more popular due to the falling CAPEX of BESS. Creative solutions are required to create stable revenue streams. Investing in BES for operating only in the FCR market might not be a sustainable business case anymore in the future. Blindly relying on maintaining current FCR prices is unwise. However, today's average FCR price must decrease by more than 75% to reach the expected average intraday market price in 2025. By combining FCR and intraday market income streams, revenues can be improved as it leads to a 35% lower capacity remuneration compared to the situation in which BES is only deployed in the FCR market. Instead of locking down to one revenue stream, BES capacity providers should steer between the two revenue streams based on price developments in these markets.

There are two major developments in the electricity market, which might increase the average capacity remuneration outside capacity provider's direct sphere of influence. First, the planned decommissioning of nuclear plants in Belgium and coal-fired power plants in Germany requires more new-build generation capacity in Europe. BES and gas-fired peaking power plants might address the shortcomings in the future, which means the average capacity remuneration rises. Second, the declining FCR price leads to lower expected incomes of BES capacity providers. This means BES capacity providers require a relatively higher capacity remuneration to cover its costs. Both factors could increase the participation of BES in the capacity market if the capacity is required to achieve the desired adequacy level.

There might be a significant gap between the low required capacity remuneration of near-zero for conventional plants as shown in other European CRMs compared to the relatively high required capacity remuneration of BES as shown in this research. To conclude, the results are not convincing regarding BES as a competitive technology in the upcoming Belgium capacity market.

9.3 Policy recommendations

The insights gained from answering the sub-questions and the main research question are translated in this section into recommendations for the Belgium CRM. The first recommendations relate to the CRM auction parameters, more specifically the strike price and the de-rating factors. Both parameters could have a significant influence on the competitiveness of BES as discussed earlier. In the minimum FCR price scenario, the difference in required capacity remuneration in the reference and optimistic scenario might be a decisive factor for competitive bidding in the CRM auction. As the CRM auction parameters are still under public consultation, Eneco should discuss the research insights on the competitiveness of BES with Elia.

The second recommendation concerns the development of the FCR price. Elia's last adequacy and flexibility study includes day-ahead market forecasts in Belgium for different CO₂ and technology scenarios. The forecasts include concrete (average) prices from 2020-2030. However, the ancillary services chapter in the study describes only price scenarios and does not provide specific prices or percentage changes. Although it might be difficult to estimate the value of ancillary services in the future, Elia has the most insight into this market through its knowledge and experience. Public price forecasts by Elia would give potential capacity suppliers a better picture of their potential income, which might increase the efficiency of the auctions. Capacity providers will be able to make a better estimate of what they need in the FCR auction and ultimately also in the CRM auction. Efficient market outcomes need relevant information for the participants.

9.4 Recommendations for further research

Several areas for further study have been discovered during the different stages of this research. The first area is related to the development of the FCR market. As mentioned in 5.4.3 there is no clear picture of how the FCR prices will develop in the future. The FCR price has a significant impact on the competitiveness of BES and therefore is a relevant area of study. However, it should be kept in mind that the FCR price is subject to many uncertain factors such as the development of renewable energy generation, residential batteries and further integration of European ancillary markets which is strongly government policy-driven. Modelling future FCR price scenarios is a very complex subject and probably interesting enough for a new master thesis. The second area is related to the feasibility of switching between the intraday market and the FCR market. Deployment strategies of the BESS could lead to optimal revenue stacking and might increase the competitiveness of BES. It is interesting to investigate whether a quantitative model can help to determine the optimal battery deployment in the intraday and FCR market, given the price developments on both markets.

This research deals with uncertainty regarding BESS CAPEX, CRM auction parameters and the FCR prices used for the scenarios. This uncertainty can be removed by adjusting the input data of the research and may require less research compared to the other two recommendations mentioned above. The accuracy of the results can be improved by using real price quotes from BESS suppliers since this research assumes estimates at the moment. The CRM rules and auction parameters will be published after this research so assumptions have been made based on other European CRMs. Using the final de-rating factor and strike price might influence the results. Furthermore, the FCR scenarios are based on the prices from on July 1, 2019, until September 30, 2019. Further integration of the European ancillary services market starts from July 2020. Therefore, the price might drop after July 2020 as discussed earlier and taking the prices over longer horizons could affect the competitiveness of BES.

10 Reflection

10.1 Scientific relevance

Scientific research has been conducted on many aspects of this study, such as the suitability of EES technologies per application, the central buyer mechanism based on reliability options and the competitiveness of EES in this capacity mechanism. Besides, the contribution of EES to the security of supply and specific market rules related to its contribution has been studied.

During the literature review, it became clear that much was already known about EES technologies and suitable applications in the electricity market. Besides, studies have already been conducted on the central buyer mechanism based on reliability options in general and the contribution of EES to the security of supply. The reflection on the Belgian de-rating factor methodology has shown that the United Kingdom has a more appropriate methodology for determining the contribution of BES based on EENS instead of LoLE. In practice, the methodology of the United Kingdom is (financially) less favorable for BES because it results in a lower capacity remuneration.

The reference price, strike price and the de-rating factor have emerged as important factors for determining the competitiveness of BES during the investigation into the Belgian CRM. The results have shown that the de-rating factor has a major impact on the minimum remuneration that BES capacity providers require. The impact of the strike price seems to be limited in this research. However, the determination of these parameters and their impact on the competitiveness are underexposed in the existing literature. This study constitutes a valuable contribution in the field of the impact of CRM auction parameters on the competitiveness of BES.

This study has shown that Linny-R is a useful, easy-to-use software tool for determining the expected income of BES. Linny-R has not been used in the past for this purpose in scientific research. The added value lies mainly in running easily and fast multiple experiments. For example, the effect of higher electricity prices, greater storage depth and an increase number of cycles on the income could easily be calculated in Linny-R.

Many elements of this study have already been discussed in literature. The scientific contribution of this research lies in the combination of from what is known from the literature, new insights into the impact of auction parameters on the competitiveness and a specific approach for assessing the competitiveness of BES in capacity markets based on reliability options.

10.2 Societal relevance

This research has been conducted in response to an actual question from Eneco whether it should participate with BES in the Belgian CRM. The constructed evaluation competitiveness model can also be used by other capacity providers to assess their competitiveness. The CRM was introduced to encourage investments in generation capacity and offers an opportunity for the storage of (sustainable) energy through BES. The social relevance lies in contributing to the formation of appropriate regulations for the Belgian CRM to create a level playing field for all capacity providers in the auction. This research shows that the strike price, de-rating factor and investment thresholds are important factors that determine the competitiveness of BES. Incorrectly estimated CRM auction parameters can reduce the participation of BES in capacity auctions, possibly in favour of existing, polluting gas-fired power plants. Even though the contribution to adequacy is a lot smaller for storage compared to conventional plants, it does contribute to making the energy sector more sustainable.

10.3 Link to the EPA programme

The EPA Master's programme focusses on the grand challenges of the 21st century. Policy, politics, modelling and simulation are the core themes to approach challenges such as flood risk, food security, clean energy and cybersecurity (TU Delft, n.d.). Battery storage is strongly related to the grand challenge and seventh United Nations sustainable development goal: affordable and clean energy for everyone (United Nations, 2015). Several EPA methods, such as problem analysis, conceptual and quantitative modelling have been conducted in this research. Subsequently, policy advice is given to Eneco based on the model outcomes, which is in line with the qualifications of an EPA thesis.

11 References

Apricum. (2018). Dentists, clouds and virtual batteries – how residential energy storage providers can drive market uptake in Germany. Retrieved from <https://www.apricum-group.com/residential-energy-storage-business-models-growth-germany/>

Arnaboldi, M., Azzone, G., & Giorgino, M. (2014). *Performance measurement and management for engineers*. Academic Press.

Askanews. (2019). Arera: tutto pronto per l'avvio del mercato della capacità. Retrieved from <https://www.askanews.it/economia/2019/09/04/arera-tutto-pronto-per-lavvio-del-mercato-della-capacità-pn-20190904-00277/>

Balci, O. (1994). Validation, verification, and testing techniques throughout the life cycle of a simulation study. *Annals of operations research*, 53(1), 121-173.

Batlle, C., & Pérez-Arriaga, I. J. (2008). Design criteria for implementing a capacity mechanism in deregulated electricity markets. *Utilities Policy*, 16(3), 184-193.

Belderbos, A., Delarue, E., & D'haeseleer, W. (2016). Calculating the levelized cost of electricity storage. In *Energy: Expectations and Uncertainty, 39th IAEE International Conference, Jun 19-22, 2016*. International Association for Energy Economics.

Belgisch Staatsblad. (2003). Wet houdende de geleidelijke uitstap uit kernenergie voor industriële elektriciteitsproductie. Retrieved from <http://www.ejustice.just.fgov.be/eli/wet/2003/01/31/2003011096/justel>

Belgische Kamer van volksvertegenwoordigers. (2019a). Wetontwerp tot wijziging van de wet van 29 april 1999 betreffende de organisatie van de elektriciteitsmarkt, teneinde een capaciteitsvergoedingsmechanisme in te stellen. Retrieved from <https://www.dekamer.be/FLWB/PDF/54/3584/54K3584007.pdf>

Belgische Kamer van volksvertegenwoordigers. (2019b). Wetsvoorstel tot wijziging van de wet van 29 april 1999 betreffende de organisatie van de elektriciteitsmarkt, teneinde een capaciteitsvergoedingsmechanisme in te stellen (verslag). Retrieved from <http://www.dekamer.be/FLWB/PDF/54/3584/54K3584004.pdf>

Bezerra, B., Barroso, L. A., Granville, S., Guimarães, A., Street, A., & Pereira, M. V. (2006). Energy call options auctions for generation adequacy in Brazil. *2006 IEEE Power Engineering Society General Meeting, Montreal, Que.*

Bezerra, B., Barroso, L. A., & Pereira, M. V. (2011). Bidding strategies with fuel supply uncertainty in auctions of long-term energy call options. *IEEE Transactions on Power Systems*, 26(2), 653-660.

Bidwell, M. (2005). Reliability options: a market-oriented approach to long-term adequacy. *The Electricity Journal*, 18(5), 11-25.

BloombergNEF. (2019a). A Behind the Scenes Take on Lithium-ion Battery Prices. Retrieved from <https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/>

BloombergNEF. (2019b). Energy Storage Investments Boom As Battery Costs Halve in the Next Decade. Retrieved from <https://about.bnef.com/blog/energy-storage-investments-boom-battery-costs-halve-next-decade/>

Bots, P.W.G. (2017). Using offsets in Linny-R expressions. Unpublished document.

CEPA. (2019). I-SEM 2022/23 T-4 Capacity Auction Independent Auction Monitor Report. Retrieved from [https://www.sem-o.com/documents/general-publications/2022-2023-T-4-Capacity-Auction Capacity-Auction-Monitor-Report REDACTED.pdf](https://www.sem-o.com/documents/general-publications/2022-2023-T-4-Capacity-Auction-Capacity-Auction-Monitor-Report-REDACTED.pdf)

Cepeda, M., & Finon, D. (2011). Generation capacity adequacy in interdependent electricity markets. *Energy Policy*, 39(6), 3128-3143.

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

Chuang, A. S., & Schwaegerl, C. (2009). Ancillary services for renewable integration. In *2009 CIGRE/IEEE PES Joint Symposium Integration of Wide-Scale Renewable Resources Into the Power Delivery System* (pp. 1-1). IEEE.

Cho, J., & Kleit, A. N. (2015). Energy storage systems in energy and ancillary markets: A backwards induction approach. *Applied Energy*, 147, 176-183.

Creswell, J. W. (2014). Research Design: Qualitative, Quantitative and Mixed Methods Approaches (4th ed.). *Thousand Oaks, CA: Sage*.

CREG. (2015). Studie over “de rentabiliteit van de elektriciteitsopslag in België”. Retrieved from
<https://www.creg.be/sites/default/files/assets/Publications/Studies/F1412NL.pdf>

CREG. (2019). Publiek raadplegingsdocument Ontwerpvoorstel (C)1907. Retrieved
<https://www.creg.be/sites/default/files/assets/Consult/2019/CRM/PRD1907NL.pdf>

DECC. (2013). Annex C: Reliability Standard Methodology. Retrieved
https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/223653/emr_consultation_annex_c.pdf

Dent, C., Wilson, A., & Zachary, S. (2017). Valuation of storage for capacity markets. University of Edinburgh. Retrieved from:
<https://www.emrdeliverybody.com/Lists/Latest%20News/Attachments/150/Duration%20Limited%20Storage%20De-Rating%20Factor%20Assessment%20-%20Final.pdf>

De Vries, L. J. (2007). Generation adequacy: Helping the market do its job. *Utilities Policy*, 15(1), 20-35.

de Vries, L., Correljé, A., & Knops, H. (2017). Electricity: Market design and policy choice. Divya, K. C., & Østergaard, J. (2009). Battery energy storage technology for power systems—An overview. *Electric power systems research*, 79(4), 511-520.

Dufo-López, R., Lujano-Rojas, J. M., & Bernal-Agustín, J. L. (2014). Comparison of different lead-acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. *Applied Energy*, 115, 242-253.

Dvorkin, Y., Fernandez-Blanco, R., Kirschen, D. S., Pandžić, H., Watson, J. P., & Silva-Monroy, C. A. (2017). Ensuring profitability of energy storage. *IEEE Transactions on Power Systems*, 32(1), 611-623.

EirGrid., & SONI. (2018). Final Capacity Auction Results 2018/2019 T-1 Capacity Auction. Retrieved from https://www.sem-o.com/documents/general-publications/Capacity-Market-Final-Capacity-Auction-Results-Report_FCAR1819T-1.pdf

EirGrid., & SONI. (2019a). Capacity Market Overview & Final 2022/2023 T-4 Auction Results Summary. Retrieved from <https://www.sem-o.com/documents/general-publications/T-4-2022-2023-Final-Capacity-Market-Auction-Overview.pdf>

EirGrid., & SONI. (2019b). Final Capacity Auction Results 2019/2020 T-1 Capacity Auction. Retrieved from <https://www.sem-o.com/documents/general-publications/T-1-2019-2020-Final-Capacity-Auction-Results-Report.pdf>

EirGrid., & SONI. (2019c). Capacity Remuneration Mechanism 2023/24 T-4 Capacity Auction Parameters. Retrieved from https://www.sem-o.com/documents/general-publications/Initial-Auction-Information-Pack_IAIP2223T-4.pdf

Elia. (n.d. -a). Primary frequency control (0-30 sec) – Frequency Containment Reserve (FCR, ex-R1). Retrieved from <http://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-services/Product-Description>

Elia. (n.d. -b). Ancillary services. Retrieved from <https://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-services>

Elia. (n.d. -c). Ancillary services. Retrieved from <https://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-services/Ancillary-Services-Volumes-Prices>

Elia. (2016a). Studie over de nood aan ‘adequacy’ en flexibiliteit in het Belgische elektriciteitssysteem. Retrieved from http://www.elia.be/~media/files/Elia/publications-2/studies/160422_ELIA_AdequacyReport_2017-2027_NL.pdf

Elia. (2017a). R2 non-CIPU. Description and conclusions of the pilot project assessment of implications of transfer of energy. Retrieved from https://www.elia.be/~media/files/Elia/users-group/Working-Group-Balancing/20171221_R2-non-CIPU-Report.pdf

Elia. (2017b). Electricity Scenarios for Belgium Towards 2050. Retrieved from https://www.elia.be/-/media/project/elia/elia-site/public-consultations/annual-report/en/20171114_elia_4584_adequacyscenario.pdf

Elia. (2018a). aFRR product design note Market Development. Retrieved from https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20180903_consultation_document_1_proposal_for_afrr_product_design_note_en.pdf

Elia. (2018b). Study on the evolution towards a daily procurement of mFRR Market Development. Retrieved from

https://www.elia.be/~media/files/Elia/publications-2/Public-Consultation/2018/22052018_Study-on-the-evolution-towards-a-daily-procurement-of-mFRR.pdf

Elia. (2018c). Proposal for an implementation plan for new aFRR design and separated procurement of FCR and aFRR. Retrieved from

https://www.elia.be/~media/files/Elia/users-group/Working-Group-Balancing/Projects%20and%20publications/R2-aFRR/20190114_Implementation-study-aFRR-final-update-feedback-stakeholders-final-without-TC.pdf

Elia. (2019a). Elia releases its figures on Belgium's 2018 energy mix. Retrieved from

http://www.elia.be/~media/files/Elia/PressReleases/2019/20190118_Press-Release-Chiffres-2018_EN.pdf

Elia. (2019b). FCR service design note Market Development. Retrieved from

<https://www.elia.be/-/media/project/elia/elia-site/electricity-market/system-services/system-services-pdf-document-library/03-balancing-services-bsp/03-fcr/02-design/2019-design-note-fcr-for-2020.pdf>

Elia. (2019c). R3 down design note. Retrieved from

https://www.elia.be/~media/files/Elia/users-group/Working-Group-Balancing/Projects%20and%20publications/20180905_Design-note-R3-down.pdf

Elia. (2019d). Electricity scenarios for Belgium towards 2050. Retrieved from

http://www.elia.be/~media/files/Elia/publications-2/studies/20190628_ELIA_Adequacy_and_flexibility_study_NL.pdf

Elia. (2019e). CRM Design Note: Derating factors. Retrieved from

<https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20191002/crm-design-note---derating-factors.pdf>

Elia. (2019f). Product Design principles - Strike & reference price. Retrieved from [https://www.elia.be/~media/files/Elia/users-group/TF CRM/08 Reference-and-Strike-price 20190426 TFCRM1.pdf](https://www.elia.be/~media/files/Elia/users-group/TF_CRM/08_Reference-and-Strike-price_20190426_TFCRM1.pdf)

Elia. (2019g). Reference & Strike price: Overview of current proposals. Retrieved from [https://www.elia.be/~media/files/Elia/users-group/TF CRM/08 20190613 TFCRM3 Strike-Reference-price.pdf](https://www.elia.be/~media/files/Elia/users-group/TF_CRM/08_20190613_TFCRM3_Strike-Reference-price.pdf)

Elia. (2019h). TF CRM. Retrieved from <https://www.elia.be/nl/users-group/Implementation%20CRM/TF%20CRM>

Elia. (2019i). Kick-off TF CRM. Retrieved from [http://www.elia.be/~media/files/Elia/users-group/20190327 Kick-off-TF-CRM.pdf](http://www.elia.be/~media/files/Elia/users-group/20190327_Kick-off-TF-CRM.pdf)

Elia. (2019j). CRM Design Note: Secondary Market. Retrieved from <https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20191002/crm-design-note---secondary-market.pdf>

Elia. (2019k). CRM Design Note: Availability Obligations and Penalties. Retrieved from [https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20190913/20190913 design note availability obligations and penalties .pdf](https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20190913/20190913_design_note_availability_obligations_and_penalties.pdf)

Elia. (2019l). Overview of Belgian CRM Design: introduction note. Retrieved from [https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20190913/20190913 overview crm design.pdf](https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20190913/20190913_overview_crm_design.pdf)

Elia. (2019m). CRM Design Note: Payback Obligation. Retrieved from <https://www.elia.be/-/media/project/elia/elia-site/public-consultations/20191002/crm-design-note-payback-obligation.pdf>

Elia. (2019n). Werkingregels voor strategische reserve Retrieved from <https://www.elia.be/-/media/project/elia/elia-site/strategic-reserve/722-adequacy-strategic-reserve/03-functioning-rules/sr-fr-2019-20-nl.pdf>

Elexys. (2019). Spot Belpex. Retrieved from <https://my.elexys.be/MarketInformation/SpotBelpex.aspx>

Eller, A. (2019). Navigant: 'Risk of slower than expected price declines' for lithium batteries but prices will fall. Retrieved from <https://www.energy-storage.news/news/navigant-risk-of-slower-than-expected-price-declines-for-lithium-batteries>

Eneco. (n.d. -a). Wind op land: productiecapaciteit (MW). Retrieved from <https://www.eneco.nl/over-ons/nieuws-en-cijfers/energiecijfers/energiebronnen/wind-op-land/>

Eneco. (n.d. -b). Wind op zee: productiecapaciteit (MW). Retrieved from <https://www.eneco.nl/over-ons/nieuws-en-cijfers/energiecijfers/energiebronnen/wind-op-zee/>

Eneco. (n.d. -c). Zon: productiecapaciteit (MW). Retrieved from <https://www.eneco.nl/over-ons/nieuws-en-cijfers/energiecijfers/energiebronnen/zon/>

Eneco. (2018). Europe's largest battery ready for its role in the energy market. Retrieved from <https://news.enecogroup.com/europes-largest-battery-ready-for-its-role-in-the-energy-market/>

Eneco. (2019). Energy Transition | Mission: sustainable energy for everyone. Retrieved from <https://www.eneco.com/who-we-are/energy-transition/>

Endesa. (2017). Endesa signs agreement with EPS to build largest electric battery system in Spain. Retrieved from <https://www.endesa.com/en/press/news/d201709-endesa-signs-agreement-eps.html>

Enel. (2018). Enel Green Power, Enertrag, Leclanché inaugurate 22 MW Cremzow battery energy storage system in Germany. Retrieved from <https://www.enel.com/media/press/d/2019/05/enel-green-power-enertrag-leclanch-inaugurate-22-mw-cremzow-battery-energy-storage-system-in-germany->

ENTSO-E. (n.d. -a). Electricity Balancing. Retrieved from https://www.entsoe.eu/network_codes/eb/

ENTSO-E. (n.d. -b). Operations. Retrieved from https://www.entsoe.eu/network_codes/sys-ops/

ENTSO-E. (2009) P1 – Policy 1: Load-Frequency Control and Performance [C]. Retrieved from https://www.entsoe.eu/fileadmin/user_upload/library/publications/entsoe/Operation_Handbook/Policy_1_final.pdf

ENTSO-E. (2018a). Explanatory note for Additional Properties of Frequency Containment Reserves. Retrieved from https://consultations.entsoe.eu/system-operations/synchronous-area-operational-agreement-policy-1-lo/supporting_documents/Article_A2_Explanatory_Note_for_Additional%20properties%20of%20FCR.pdf

ENTSO-E. (2018b). Electricity balancing in Europe. An overview of the European balancing market and electricity balancing guideline. Retrieved from https://docstore.entsoe.eu/Documents/Network%20codes%20documents/NC%20EB/entso-e_balancing_in%20_europe_report_Nov2018_web.pdf

Energy Storage Association. (n.d. -a). Grid Operations Benefits. Retrieved from <http://energystorage.org/energy-storage/energy-storage-benefits/benefit-categories/grid-operations-benefits>

Energy Storage News. (2019). UK's evolving ESS market likely to take installed base above 1.2GW this year. Retrieved from <https://www.energy-storage.news/blogs/uks-evolving-business-models-likely-to-take-installed-base-above-1.2gw-this>

EPEX SPOT. (n.d. -a). Latest Market Results. Retrieved from <https://www.belpex.be/>

EPEX SPOT. (n.d. -b). EPEX SPOT DAM. Retrieved from <https://www.belpex.be/trading-clearing/dam/>

EPEX SPOT. (n.d. -c). EPEX SPOT CIM. Retrieved from <https://www.belpex.be/trading-clearing/belpex-cim/>

EPEX SPOT. (n.d. -d). Belgian SRM. Retrieved from <https://www.belpex.be/trading-clearing/belpex-srm/>

EPEX SPOT. (n.d. -e). Product specifications. Retrieved from <https://www.belpex.be/trading/product-specification/>

European Commission. (n.d.). State aid to secure electricity supplies. Retrieved from http://ec.europa.eu/competition/sectors/energy/state_aid_to_secure_electricity_supply_en.html

European Commission. (2015). Capacity Mechanisms Working Group: High level comparison of capacity mechanism models and compatibility with state aid guidelines. Retrieved from http://ec.europa.eu/competition/sectors/energy/capacity_mechanisms_working_group_10_en.pdf

European Commission. (2017a). State aid No. SA.44464 (2017/N) – Ireland Irish Capacity Mechanism. Retrieved from http://ec.europa.eu/competition/state_aid/cases/267880/267880_1948214_166_2.pdf

European Commission. (2017b). Commission regulation (EU) 2017/2195 of 23 November 2017 establishing a guideline on electricity balancing. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R2195&from=EN>

European Commission. (2017c). COMMISSION REGULATION (EU) 2017/1485. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1485&from=EN>

European Commission. (2018). State Aid SA.42011 (2017/N) – Italy – Italian Capacity Mechanism. Retrieved from http://ec.europa.eu/competition/state_aid/cases/270875/270875_1979508_218_2.pdf

European Parliament and of the Council (2019). On the internal market for electricity. (Regulation 2019/943). Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32019R0943&from=FR>

Evans, A., Strezov, V., & Evans, T. J. (2012). Assessment of utility energy storage options for increased renewable energy penetration. *Renewable and Sustainable Energy Reviews*, 16(6), 4141-4147.

Evans, M. P., Tindemans, S. H., & Angeli, D. (2019). Minimising Unserved Energy Using Heterogeneous Storage Units. *IEEE Transactions on Power Systems*, 34(5), 3647–3656.

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

Finon, D., & Pignon, V. (2008). Electricity and long-term capacity adequacy: The quest for regulatory mechanism compatible with electricity market. *Utilities Policy*, 16(3), 143-158.

FOD Economie (2015). Studie inzake de mogelijkheden tot opslag van elektriciteit die in België kunnen worden aangewend op de korte, middellange en lange termijn teneinde bij te dragen tot de bevoorradingszekerheid van elektriciteit. Retrieved from <https://anzdoc.com/studie-inzake-de-mogelijkheden-tot-opslag-van-elektriciteit.html>

Genc, T. S. (2012). Equilibrium predictions in wholesale electricity markets. *Handbook of Networks in Power Systems I*, 263-279.

Gonzalez-Salazar, M. A., Kirsten, T., & Prchlik, L. (2018). Review of the operational flexibility and emissions of gas-and coal-fired power plants in a future with growing renewables. *Renewable and Sustainable Energy Reviews*, 82, 1497-1513.

Hancher, L., de Hauteclocque, A., & Sadowska, M. (2015). *Capacity mechanisms in the EU energy market: law, policy, and economics*. Oxford: Oxford University Press.

Harbord, D., & Pagnozzi, M. (2014). Britain's electricity capacity auctions: lessons from Colombia and New England. *The Electricity Journal*, 27(5), 54-62.

Henriques, M. V., & Stikkelman, R. M. (2017). Assessing storage and substitution as power flexibility enablers in industrial processes. In *2017 14th International Conference on the European Energy Market (EEM)* (pp. 1-6). IEEE.

Hu, W., Chen, Z., & Bak-Jensen, B. (2010). Optimal operation strategy of battery energy storage system to real-time electricity price in Denmark. In *IEEE PES general meeting* (pp. 1-7). IEEE.

Ho, T. S., & Lee, S. B. (2004). *The Oxford Guide to Financial Modeling: Applications for Capital Markets, Corporate Finance, Risk Management and Financial Institutions*. Oxford University Press.

IEA (2018). World Energy Outlook 2018. Retrieved from <https://www.iea.org/weo2018/>

Ibrahim, H., Ilinca, A., & Perron, J. (2008). Energy storage systems—Characteristics and comparisons. *Renewable and sustainable energy reviews*, 12(5), 1221-1250.

Infigen (2018). Lake Bonney Battery Energy Storage System. Retrieved from <https://www.infigenenergy.com/lake-bonney-battery-energy-storage-system-0/>

IRENA (2017). Electricity Storage and Renewables: Costs and Markets to 2030, International Renewable Energy Agency, Abu Dhabi. Retrieved from <https://www.irena.org/publications/2017/Oct/Electricity-storage-and-renewables-costs-and-markets>

Karloff, H. (2008). *Linear programming*. Springer Science & Business Media.

KBC. (2018). Dit moet u weten over de nieuwe vennootschapsbelasting. Retrieved from <https://www.kbc.be/ondernemen/nl/nieuws/zaak-praktijk-en-u/nieuwe-vennootschapsbelasting.html>

Konstantelos, I., & Strbac, G. (2018). Capacity value of energy storage in distribution networks. *Journal of Energy Storage*, 18, 389-401.

Liljeblom, E., & Vaihekoski, M. (2004). Investment evaluation methods and required rate of return in Finnish publicly listed companies. *Finnish Journal of Business Economics*, 53(1).

Limpens, G., & Jeanmart, H. (2018). Electricity storage needs for the energy transition: An EROI based analysis illustrated by the case of Belgium. *Energy*, 152, 960-973.

Lu, C. C., Ying, K. C., & Chen, H. J. (2016). Real-time relief distribution in the aftermath of disasters—A rolling horizon approach. *Transportation research part E: logistics and transportation review*, 93, 1-20.

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

Mercier, P., Cherkaoui, R., & Oudalov, A. (2009). Optimizing a battery energy storage system for frequency control application in an isolated power system. *IEEE Transactions on Power Systems*, 24(3), 1469-1477.

Meulman, L., & Méray, N. (2012). Capacity Mechanisms in Northwest Europe. Between a Rock and a Hard Place. Retrieved from http://www.clingendaelenergy.com/inc/upload/files/Capacity_mechanisms.pdf

Mulder, M. (2017). Energietransitie en elektriciteitsmarkt: verkenning van een gespannen relatie. *Policy Papers*, 1, 3-68.

National Grid. (2015). Final Auction Results. T-4 Capacity Market Auction for 2019/20. Retrieved from <https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-4%202015%20Final%20Results%20Report.pdf>

National Grid. (2016). Final Auction Results. T-4 Capacity Market Auction for 2020/21. Retrieved from <https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-4%202016%20Final%20Results%20Report.pdf>

National Grid. (2017). Duration-Limited Storage De-Rating Factor Assessment – Final Report. Retrieved from <https://www.emrdeliverybody.com/Lists/Latest%20News/Attachments/150/Duration%20Limited%20Storage%20De-Rating%20Factor%20Assessment%20-%20Final.pdf>

National Grid. (2018a). Final Auction Results. T-1 Capacity Market Auction for 2018/19. Retrieved from

<https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-1%202017%20Final%20Results%20Report.pdf>

National Grid. (2018b). Final Auction Results. T-4 Capacity Market Auction for 2021/22. Retrieved from

<https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-4%202017%20Final%20Results%20Report.pdf>

National Grid. (2018c). Capacity Market Auction Guidelines. 2018 year ahead Capacity Auction (T-1) and 2018 four year ahead Capacity Auction (T-4). Retrieved from

<https://www.emrdeliverybody.com/Lists/Latest%20News/Attachments/197/Auction%20Guidelines%202018%20v2.0.pdf>

National Grid. (2019). Final Auction Report 2018 year ahead Capacity Auction (T-1) Delivery year 2019/20. Between a Rock and a Hard Place. Retrieved from

[https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-1%202018%20Final%20Results%20Report%20\(DY%2019-20\).pdf](https://www.emrdeliverybody.com/Capacity%20Markets%20Document%20Library/T-1%202018%20Final%20Results%20Report%20(DY%2019-20).pdf)

Newbery, D. (2016). Missing money and missing markets: Reliability, capacity auctions and interconnectors. *Energy Policy*, 94, 401-410.

Oudalov, A., Chartouni, D., & Ohler, C. (2007). Optimizing a battery energy storage system for primary frequency control. *IEEE Transactions on Power Systems*, 22(3), 1259-1266.

Pena-Alzola, R., Sebastián, R., Quesada, J., & Colmenar, A. (2011). Review of flywheel based energy storage systems. In *2011 International Conference on Power Engineering, Energy and Electrical Drives* (pp. 1-6). IEEE.

Pérez-Arriaga, I. J. (1999). Reliability and generation adequacy. *IEEE Power Engineering Review*, 19(12), 6-9.

Poullikkas, A. (2013). A comparative overview of large-scale battery systems for electricity storage. *Renewable and Sustainable energy reviews*, 27, 778-788.

PwC. (2018). Bepaling van het mechanisme voor de vergoeding van capaciteit voor België en de voorbereiding van het wettelijk kader. Retrieved from <https://economie.fgov.be/sites/default/files/Files/Energy/Rapport-Bepaling-van-het-mechanisme-voor-de-vergoeding-van-capaciteit-voor-Belgie-en-de-voorbereiding-van-het-wettelijk-kader.pdf>

Regelleistung. (n.d. -a). Tender overview. Retrieved from <https://www.regelleistung.net/ext/static/prl?lang=en>

Regelleistung. (n.d. -b). Datacenter FCR/aFRR/mFRR. Retrieved from <https://www.regelleistung.net/apps/datacenter/tenders/>

Rozporządzenie Ministra Energii. (2018). w sprawie parametrów aukcji głównych dla okresów dostaw przypadających na lata 2021–2023. Retrieved from <http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20180001632/O/D20181632.pdf>

RTE. (2019). Continental Europe synchronous area frequency data metered by RTE 2019. Retrieved from <https://clients.rte-france.com/servlets/FrequenciesServlet?annee=2019>

Sioshansi, R., Madaeni, S. H., & Denholm, P. (2013). A dynamic programming approach to estimate the capacity value of energy storage. *IEEE Transactions on Power Systems*, 29(1), 395-403.

Soloveichik, G. L. (2011). Battery technologies for large-scale stationary energy storage. *Annual review of chemical and biomolecular engineering*, 2, 503-527.

Statbel. (2019). Consumptieprijnsindex. Retrieved from <https://statbel.fgov.be/nl/themas/consumptieprijnsindex/consumptieprijnsindex>

Terna. (2019). July 2019 Monthly Report on the Electricity System. Retrieved from https://download.terna.it/terna/Monthly%20Report%20on%20the%20Electricity%20System_July%202019_8d732d20b82a06f.pdf

Thirugnanam, K., Saini, H., & Kumar, P. (2012). Mathematical modeling of Li-ion battery for charge/discharge rate and capacity fading characteristics using genetic algorithm approach. *2012 IEEE Transportation Electrification Conference and Expo (ITEC)*, 1-6.

TU Delft. (n.d.). MSc Engineering and Policy Analysis. Retrieved from <https://www.tudelft.nl/onderwijs/opleidingen/masters/epa/msc-engineering-and-policy-analysis/>

United Nations. (2015). Sustainable Development Goals: Ensure access to affordable, reliable, sustainable and modern energy. Retrieved from <https://www.un.org/sustainabledevelopment/energy/>

UNFCCC. (2015). Paris Agreement. Retrieved from <https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement>

US DOE. (2017). DOE Global Energy Storage Database. United States Department of Energy. Office of Electricity & Energy Reliability. Retrieved from https://www.irena.org/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf

Valenzuela, J., & Mazumdar, M. (2001). Monte Carlo computation of power generation production costs under operating constraints. *IEEE Transactions on Power Systems*, 16(4), 671-677.

Van den Bergh, K., Bruninx, K., Delarue, E., & D'haeseleer, W. (2014). A mixed-integer linear formulation of the unit commitment problem. *WP EN2014-07*.

Vázquez, C., Rivier, M., & Pérez-Arriaga, I. J. (2002). A market approach to long-term security of supply. *IEEE Transactions on power systems*, 17(2), 349-357.

Vázquez, C., Batlle, C., Rivier, M., & Pérez-Arriaga, I. J. (2003). Security of supply in the Dutch electricity market: the role of reliability options. Retrived from <https://www.iit.comillas.edu/batlle/Docs/2003%20Security%20of%20supply%20in%20the%20Dutch%20electricity%20market%20The%20role%20of%20reliability%20options.pdf>

VREG. (2019). Marktgegevens elektriciteit 2019: Marktaandelen actieve leveranciers. Retrieved from https://www.vreg.be/sites/default/files/statistieken/marktaandelen/20190312-e-nl-martkaandeel_maandelijks_netbeheerderds_h_plus_nh.pdf

Wang, W., Li, C., Liao, X., & Qin, H. (2017). Study on unit commitment problem considering pumped storage and renewable energy via a novel binary artificial sheep algorithm. *Applied energy*, 187, 612-626.

World Bank. (2019). Four Things You Should Know About Battery Storage. Retrieved from <https://www.worldbank.org/en/news/feature/2019/05/16/four-things-you-should-know-about-battery-storage>

XE. (2019). XE Currency Converter. Retrieved from <https://www.xe.com/currencyconverter/convert/?Amount=1&From=EUR&To=USD>

Zhou, Y., Mancarella, P., & Mutale, J. (2015). Modelling and assessment of the contribution of demand response and electrical energy storage to adequacy of supply. *Sustainable Energy, Grids and Networks*, 3, 12-23.

12. Appendices

12.1 Full cycle definition

An important performance characteristic for the lifetime of batteries is the cycle life. The cycle life is defined as the number of (full round) charge and after that discharge cycles before it no longer meets performance standards (Thirugnanam, Saini, & Kumar, 2012). It is also closely related to the storage costs because of the more cycles a battery performs, the shorter the battery's lifetime, which increases the storage costs. The cycling process of charging and discharging is shown in figure 14.

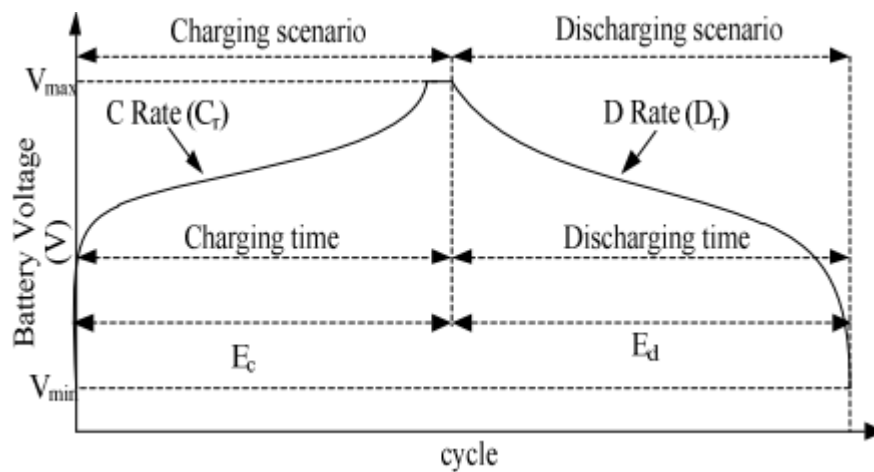


Figure 28. Cycling process (Thirugnanam, Saini, & Kumar, 2012).

In this research, the definition of an equivalent full-cycle refers to the full charge, and after that, the full discharge of a BESS with one hour of storage depth. Batteries with a greater storage depth require fewer (full) cycles for the same operation in the energy market. For BESS with greater storage depth, the number of performance cycles should be divided by the hours of storage depth.

Suppose, a BESS is deployed in the FCR market and is obligated to make 160 cycles per year. According to the definition in this research, a BESS with 1 hour of storage depth requires 160 cycles but a BESS with 2 hours of storage depth requires 80 cycles and a BESS with 4 hours requires 40 cycles etc.

12.2 Intraday market

12.2.1 Input prices

The table below shows, as an example, first the 24 hours intraday market prices of the years 2020-2030. 2018 is the initial year. The prices for 2020, 2023, 2025, 2028 and 2030 has been calculated based on the price scenarios mentioned in 5.2.1.

2018-2020: -20,4%

2020-2023: +13,6%

2023-2025: -2%

2025-2028: -8,2%

2028-2030: +13,3%

The prices of 2021, 2022, 2025, 2026, 2027 and 2029 are approximated through linear interpolation between the calculated years.

Date	2018	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
1-01-18 0:00	25,00	19,90	20,80	21,70	22,61	22,38	22,15	21,55	20,94	20,34	21,69	23,04
1-01-18 1:00	25,00	19,90	21,25	22,16	22,61	22,38	22,15	21,55	20,94	20,34	21,69	23,04
1-01-18 2:00	-0,74	-0,59	-0,63	-0,65	-0,67	-0,66	-0,65	-0,64	-0,62	-0,59	-0,64	-0,68
1-01-18 3:00	11,81	9,40	10,04	10,47	10,68	10,58	10,47	10,18	9,90	9,61	10,25	10,89
1-01-18 4:00	-5,52	-4,39	-4,69	-4,89	-4,99	-4,94	-4,89	-4,76	-4,62	-4,49	-4,79	-5,09
1-01-18 5:00	-34,76	-27,67	-29,55	-30,81	-31,44	-31,12	-30,81	-29,96	-29,12	-28,28	-30,16	-32,04
1-01-18 6:00	-20,36	-16,20	-17,30	-18,04	-18,41	-18,22	-18,04	-17,55	-17,05	-16,56	-17,66	-18,76
1-01-18 7:00	-22,99	-18,30	-19,55	-20,38	-20,79	-20,58	-20,37	-19,82	-19,26	-18,70	-19,95	-21,19
1-01-18 8:00	-16,14	-12,84	-13,72	-14,30	-14,59	-14,45	-14,30	-13,91	-13,52	-13,13	-14,00	-14,87
1-01-18 9:00	-12,29	-9,78	-10,45	-10,89	-11,11	-11,00	-10,89	-10,59	-10,30	-9,99	-10,66	-11,33
1-01-18 10:00	-8,45	-6,72	-7,18	-7,48	-7,64	-7,56	-7,48	-7,28	-7,08	-6,87	-7,33	-7,78
1-01-18 11:00	-4,60	-3,66	-3,91	-4,08	-4,16	-4,12	-4,08	-3,96	-3,85	-3,74	-3,99	-4,24
1-01-18 12:00	16,45	13,09	13,98	14,57	14,87	14,72	14,57	14,17	13,78	13,38	14,27	15,16
1-01-18 13:00	12,52	9,97	10,64	11,10	11,32	11,21	11,09	10,79	10,49	10,19	10,86	11,54
1-01-18 14:00	15,11	12,03	12,85	13,39	13,67	13,53	13,39	13,03	12,66	12,30	13,11	13,93
1-01-18 15:00	20,68	16,46	17,58	18,33	18,70	18,51	18,33	17,83	17,33	16,82	17,94	19,06
1-01-18 16:00	31,86	25,36	27,08	28,23	28,81	28,52	28,23	27,46	26,69	25,91	27,64	29,36
1-01-18 17:00	51,80	41,24	44,04	45,91	46,84	46,37	45,91	44,65	43,40	42,14	44,94	47,75
1-01-18 18:00	63,08	50,21	53,63	55,91	57,04	56,47	55,90	54,37	52,85	51,32	54,73	58,14
1-01-18 19:00	76,87	61,19	65,35	68,12	69,51	68,81	68,12	66,26	64,39	62,53	66,69	70,85
1-01-18 20:00	71,53	56,94	60,81	63,39	64,68	64,04	63,39	61,66	59,93	58,19	62,06	65,93
1-01-18 21:00	56,91	45,30	48,38	50,44	51,46	50,95	50,43	49,05	47,68	46,30	49,38	52,45
1-01-18 22:00	24,99	19,90	21,25	22,15	22,60	22,37	22,15	21,54	20,94	20,33	21,68	23,04
1-01-18 23:00	25,94	20,65	22,06	22,99	23,46	23,23	22,99	22,36	21,73	21,11	22,51	23,91

12.2.2 Income build year 2020

Assuming (maximum) 301 full equivalent cycles per year and 1-hour storage depth.

Year	Intraday market income[€/MW/year]
2021	15.957
2022	16.750
2023	16.934
2024	16.685
2025	16.749
2026	16.119
2027	15.768
2028	15.269

12.2.3 Income build year 2025

Assuming (maximum) 379 full equivalent cycles per year and 1-hour storage depth.

Year	Intraday market income[€/MW/year]
2026	17.860
2027	17.358
2028	16.856
2029	18.633
2030	18.780
2031	18.780
2032	18.780
2033	18.780

Assuming (maximum) 379 full equivalent cycles per year and 2-hour storage depth.

Year	Intraday market income[€/MW/year]
2026	22.434
2027	21.920
2028	21.376
2029	23.509
2030	23.817
2031	23.817
2032	23.817
2033	23.817

12.2.4 Income build year 2030

Assuming (maximum) 479 full equivalent cycles per year and 1 hour storage depth

Year	Intraday market income[€/MW/year]
2031	17.860
2032	17.860
2033	17.860
2034	17.860
2035	17.860
2036	17.860
2037	17.860
2038	17.860

12.3 FCR market

12.3.1 Cycles and energy delivery on FCR market

The table below shows the parameters and values assumed for calculating the minimum (full equivalent) cycles to meet the FCR requirements.

parameters	Value	Unit
Nominal frequency	50	[Hz]
Minimum frequency deviation	0,01	[Hz]
Maximum frequency deviation	0,2	[Hz]
time unit	360	[s]
correction factor (<i>1/ time unit</i>)	0,002778	[1/s]
Initial state of charge	3,35	[MWh]
Energy capacity	6,7	[MWh]
Minimum State of Charge	2,5	[MWh]
Maximum State of Charge	4,2	[MWh]

A snapshot of the frequency data of 2018 is presented in the table below and shows the first 5 entries (RTE, 2019).

Date [dd/mm/y hh:mm]	Frequency [Hz]	F deviation [Hz]	Energy regulation [MWh]	State [MWh]	Up regulation [MWh]	Down regulation [MWh]
1-1-2018 00:00	50,0252	0,0252	0,000368421	3,35	0	0
1-1-2018 00:00	50,0138	0,0138	0,000201754	3,350368421	0,000368421	0
1-1-2018 00:00	49,9983	-0,0017	0	3,350570175	0,000201754	0
1-1-2018 00:00	49,9942	-0,0058	0	3,350570175	0	0
1-1-2018 00:00	49,9978	-0,0022	0	3,350570175	0	0

The values in the column F deviation, energy regulation, state, up regulation and down regulation are calculated as follows:

Note: If statements are written in the form: *IF(logical test; value if true; value if false)* and *t-1* indicates the previous time step if applicable. Besides, the State in the first row is the initial state.

- **Date:** the date is available per 10 seconds for the year 2018;
- **Frequency:** the measured frequency;
- **F deviation:** *Frequency – Nominal frequency* ;
- **Energy regulation:**

$$\frac{IF(|F \text{ deviation}| > \text{minimum frequency deviation}; \frac{F \text{ deviation}}{(\text{maximum frequency deviation} - \text{minimum frequency deviation}) * \text{correction factor}}; 0);$$

- **State:**

$$IF(\text{State}_{t-1} + \text{Energy regulation}_{t-1} > \text{Maximum State of Charge}; \\ \text{State}_{t-1} + \text{Energy regulation}_{t-1} - \text{correction factor}; \\ IF(\text{State}_{t-1} + \text{Energy regulation}_{t-1} \\ < \text{Minimum State of Charge}; \text{State}_{t-1} + \text{Energy regulation}_{t-1} \\ + \text{correction factor}; \text{State} + \text{Energy regulation}))$$

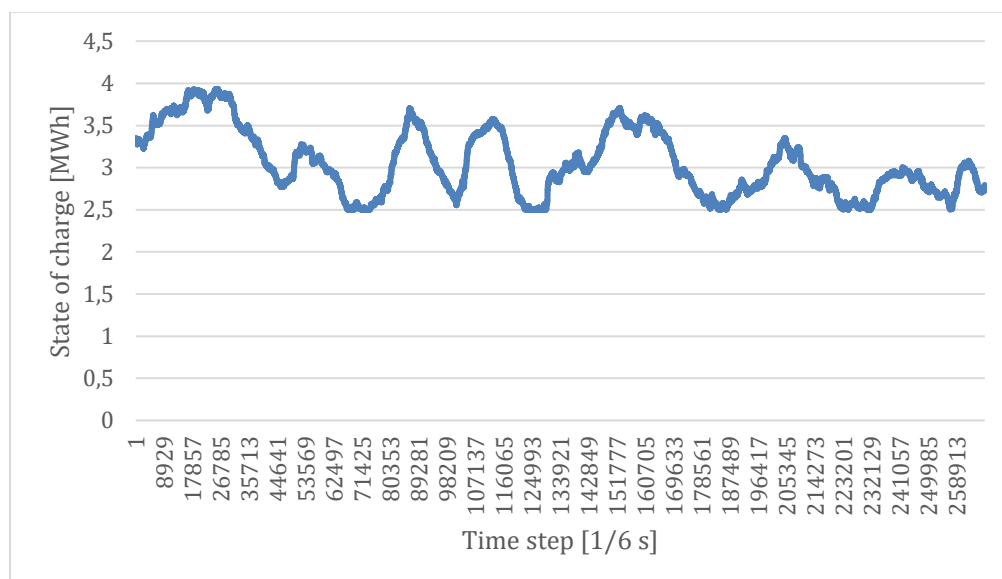
- **Up regulation:**

$$IF(\text{State} - \text{State}_{t-1} > 0; \text{State} - \text{State}_{t-1}; 0)$$

- **Down regulation:**

$$IF(\text{State} - \text{State}_{t-1} < 0; \text{State} - \text{State}_{t-1}; 0)$$

As an example, the state of charge of the BESS is calculated based on the frequency data of January 2018 and the assumptions above and plotted in the figure below.



The table below shows the required (full equivalent) cycles upwards and downwards per month and the full (paid) charges in MWh to maintain the minimum state of charge of 2,5 MWh.

Month	Upwards cycles	Downwards cycles	Full (paid) charges in MWh
January	29	-28	1,525321637
February	34	-35	15,30648538
March	43	-41	4,681434211
April	35	-35	1,666209064
May	27	-28	2,383605263
June	25	-25	0,465959064
July	28	-28	3,473038012
August	26	-25	0,08530848
September	28	-29	1,040134503
October	32	-30	1,858913743
November	27	-29	0,295216374
December	28	-28	1,55780117
<u>Total</u>	362,26	-361,72	34,3394269

12.3.2 Price scenarios

Assuming (maximum) 362 full equivalent cycles per year and 1-hour storage depth. Prices are based on capacity prices since the introduction of the regional FCR auction on July 1, 2019 till September 30, 2019.

Price scenario	FCR income [€/MW/year]
Average FCR price (€ 215,83/MW/day)	78.779
Min. FCR price (€ 140,33/MW/day)	51.220
50% of the average FCR price (€ 106,78/MW/day)	39.390