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Social Economic Welfare effects of Large-Scale Energy Storage and relation with Variable Renewable Energy Sources Shares

ENERGY SCIENCE MASTER'S THESIS – FINAL REPORT

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Summary

The widespread integration of Variable Renewable Energy Sources (VRES) into the power system represents a challenge due to their variability and stochasticity. Large-Scale Energy Storage Systems (ESS) are emerging as key technologies to support the VRES integration and the reliability, flexibility, and sustainability of power systems. Understanding the value, revenue streams, and implications of Large-Scale deployment of ESS is important for investors, policy makers, and market regulators to assess their potential role in the current and future power systems as well as to better promote their deployment and integration.

The present study aimed to add to the discussion by assessing how large-scale ESS affect the social economic welfare (SEW) in the present and future wholesale electricity markets by studying its effect under different VRES penetration levels. In order to answer the research question, the present study modelled the Belgian Day Ahead (DA) wholesale electricity market-clearing in which the existing Pumped Hydro Electricity Storage (PHES) capacity was simulated next to different sizes of large-scale Battery Energy Storage Systems (BESS) for varying VRES shares. To achieve the previous, a model incorporating multiple merchant-owned large-scale ESS into the DA wholesale electricity market was developed considering two perspectives: the ESS players´ and the Market Operator´s. For the former, the price-maker ESS players´ bidding strategy was modelled as a bilevel optimization with the objective of profit maximization. For the latter, the DA market was cleared in a SEW-maximizing way based on the bids submitted by the generators, consumers and ESS players, obtaining the market-clearing prices and the traded quantity.

For each simulated scenario, the SEW, producer surplus, consumer surplus, and ESS Net Revenue were calculated. The difference in the resulting SEW and shifts in consumer and producer surplus were then analysed.

The results showed that large-scale ESS can have a significant impact for all market participants of the electricity market in comparison to the no storage case by levelling the differences in the on-peak and off-peak Market Clearing Price (MCP) and avoiding the use of expensive generation. With the increasing VRES participation in the generation mix, ESS systems have the potential of significantly improving the SEW by levelling the extreme maximum and minimum prices caused by the daily cycles of the solar generation.

Regarding the effects of the price-maker ESS operation, the research found that the price-maker ESS player's profit maximizing objective does not always align with the optimal solution from the SEW perspective and can lead to limited use of the storage capacity.

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Acronyms and Abbreviations

Acronym	Definition
BE	Belgium
BESS	Battery Energy Storage System
BRP	Balance Responsible Party
CAES	Compressed Air Energy Storage
ACAES	Adiabatic Compressed Air Energy Storage
CAPEX	Capital Expenditures
CS	Consumer Surplus
CWE	Central Western European
DA	Day Ahead
DE-LU	Germany-Luxembourg
ESS	Energy Storage System
FCR	Frequency containment reserve
FRR	Frequency restauration reserve
FR	France
ID	Intraday
IRENA	International Renewable Energy Agency
KKT	Karush-Kuhn-Tucker
LAES	Liquid Air Energy Storage
LVRES	Large Variable Renewable Energy Sources Participation
MCP	Market Clearing Price
MILP	Mixed-integer linear programming
MINLP	Mixed Integer Non-Linear Program
MPCC	Mathematical Program with Complementarity Constraints
NL	Netherlands
PHES	Pumped Hydro Energy Storage
PS	Producer Surplus
PTES	Pumped Thermal Energy Storage
RT	Real Time
SEW	Social Economic Welfare
SWPHS	Seawater Pumped Hydro Storage
TSO	Transmission System Operator
UK	United Kingdom
UPHES	Underground Pumped Hydro Storage
UU	Utrecht University
VRES	Variable Renewable Energy Sources

1 Introduction

The world has seen an increase in the role of Variable Renewable Energy Sources (VRES) in the electricity generation mix in an attempt to reduce greenhouse gases emissions and meet the climate goals set in the Paris Agreement. However, their widespread integration into the power system represents a challenge due to their variability and stochasticity that makes balancing the supply and the demand a complex process. Energy storage has been identified as one of the potential solutions [1]–[3].

Large-Scale Energy Storage Systems (ESS), also referred as grid-scale or utility-scale ESS, are emerging as key technologies to ensure the reliability, flexibility, and sustainability of power systems [3], [4]. The ESS' ability to quickly absorb, store, and reinject electricity can provide various grid services such as peak shaving, frequency regulation, flexible ramping, black start services, transmission and distribution congestion relief, reduced VRES curtailment, and peak capacity [5], [6]. Understanding the value and implications of Large-Scale ESS for the different applications is important for investors, policy makers, and market regulators to assess their potential role in the current and future power systems as well as to better promote their deployment and integration.

For the peak shaving and energy shifting applications, ESS charge when there is low demand and discharge during peak hours. The previous entails that the ESS buy the energy from the wholesale electricity market at a low off-peak price and sell it at a high on-peak price, benefiting from the price difference. This is known as energy arbitrage [5], [7].

Extensive research has been carried out in relation to the value of energy storage for energy arbitrage applications. However, this has mostly been from the owner's perspective. There is less literature quantifying the value of storage from a societal perspective. Some authors [8]–[12] have explored the effects of large-scale energy storage inclusion in the Social Economic Welfare (SEW) of the power system, as well as the influence of market power and ESS ownership in the results. These analyses generally found an increased SEW as a result of large-scale ESS.

Most of the research found regarding the impact of large-scale ESS in SEW was carried out between 2009 and 2014. Since then, the role of VRES in electricity generation has increased, and it is expected to continue increasing [6]. The growing penetration of VRES in the power system also leads to changes in the wholesale electricity market, generally reducing market-clearing prices and generators' profits [13].

The present study aimed to add to the discussion by developing a model to assess how large-scale price-maker ESS affect the SEW in the present and future wholesale electricity markets by studying its effect under different storage and VRES penetration levels. The last was done using the information from the Belgian electricity market.

Specifically, this research answers the following question:

"What are the effects of large-scale ESS integration into the Day-Ahead (DA) market on the SEW under different VRES penetration levels in the Belgian electricity market? "

To be able to answer the main research question, the following sub-questions were identified:

1. How can the Belgian Day-Ahead electricity market be modelled?
2. How can ESS's scheduling, and bidding decisions be incorporated into the above market-clearing model?
3. How do ESS affect the market clearing price in the present and projected scenarios?
4. What are the SEW, consumer surplus, and producer surplus implications?
5. What do the results mean to market participants and regulators?

2 Theoretical Background

To perform the analysis, it is important to first understand the energy storage technologies used for peak shaving and energy shifting and their main characteristics. This section will also review the key concepts of the electricity markets and the role of the energy storage participation in these.

2.1 Energy Storage

Energy storage can be deployed at different scales and with different characteristics to serve one or various applications such as bulk energy services, ancillary services, transmission infrastructure services, distribution infrastructure services, customer energy management services, as well as off-gird and transport services.

The system services that ESS can provide have varying timescales and magnitude. Energy storage discharge time can range from seconds to months. Therefore, a storage technology needs to have the appropriate technical characteristics to effectively fulfil a specific application. The main characteristics to consider when defining suitability for an application normally are the size, response time, power capacity, energy capacity, and discharge duration *(duration[h] = Energy Capacity [kWh]/Power Rating [kW])* [6], [14]. However, other technical and economic characteristics such as efficiency, energy density, and investment and operating costs are also relevant when evaluating economic viability [6].

The present study will focus in the ESS provision of bulk energy services, specifically energy shifting and peak shaving. By providing this service, storage can minimize the energy curtailed from VRES and avoid the start-up of costly peak generators in times of high demand [5], [14], [15], supporting the integration of VRES and the achievement of climate goals. The provision of this service usually needs ESS installations with a size between 10 MW and 1000 MW and a discharge duration from 3 to 10 hours. The next section will explore the technologies currently used or proposed for these applications.

2.1.1 Energy Storage Technologies

Energy shifting needs have historically been met mostly by Pumped Hydro Energy Storage (PHES) due to its relatively high round-trip efficiency, large storage capacity, long lifetime, and low costs of storage. However, geographic restrictions and social and environmental concerns related to its extensive land use and the impact on the river s' flow rates are limiting factors for the continued capacity expansion for this technology. As a result, alternative water-based storage technologies are being studied. Some examples are the Seawater Pumped Hydro Storage (SWPHS) and the use of underground reservoirs (UPHES) [14].

Compressed Air Energy Storage (CAES) is another storage technology commonly considered for the studied application. This technology stores energy in the form of compressed air in a reservoir, which can be a conditioned old natural salt deposit or a depleted gas-field. While a purpose-built cavern can be used, this considerably increases the storage costs [14]. Even though CAES technologies have been widely studied, there are still few existing installations and projects under development due to the required specific geographic conditions and costs uncertainties [1].

Although batteries had not been widely studied for energy shifting and peak shaving applications, they are increasingly interesting technologies in this field. While these technologies were too costly in the past for utility-scale storage systems, technology developments have led to significant cost reductions and higher energy densities. Additionally, unlike PHES and CAES, batteries offer geographical and sizing flexibility. Because of the previous, the utility-scale market for BESS is expected to grow strongly in the following years, with projects managed individually or in an aggregated way so that they become a virtual large-scale system [16]. Some of the most studied batteries technologies are Sodium sulphur (NaS), Lithium-ion (Li-ion), and flow batteries[1]. Each of these technologies, however, has its challenges such as high operating temperatures that need to be managed, cell degradation, and high maintenance costs due to moving parts, respectively.

Other energy storage technologies being researched are the Liquid Air Energy Storage (LAES), and Brayton and Rankine Pumped Thermal Energy Storage (Ra-PTES and Ba-PTES, respectively), more information on these and further description of the mentioned storage technologies can be found at [14].

Table 1 summarizes the technologies currently being explored for energy shifting applications as well as some of its technical and economical characteristics.

Table 1. Technical and economic characteristics of electricity storage technologies for energy shifting. Where P stands for Power rating, C for energy capacity, ρ_{en} for energy density, τ_r for response time, η rt for round-trip efficiency, L for lifetime, and TRL for Technology Readiness Level [14].

Technology	P [MW]	C [MWh]	ρ_{en}[kWh/m³]	τ_r [min]	η rt [%]	L [years]	TRL	Power cost [€/kW]	Capacity cost [€/kWh]
PHES	100 +	1000+	0.5-1.5	1-3	65-85	30-40+	9	400/600-1000/2000	1/5-100
UPHES	100 +	1000+	0.5-1.5	1-3	70-85	30-40+	2	400/600-1000/2000	85
SWPHES	30+	200+	0.3-0.4	1-3	70-85	15+	7-8	720-2200	25-30
CAES[a]	-	-	-	-	60-70	20-40	9	400/500-800/1000	1/2-50/100/200
ACAES	100	360+	0.5-20	10-15	60-70	20-40	5	700-1000	40-80
Br-PTES	1-10+	1-60+	110-200	1-3	50-70	20-40	4-5	600-800	20/90-60/180
Ra-PTES	1-10+	1-60+	140-170	1-3	40-60	20-40	4-5	225/390-450	45-95/120
NaS Batt.	1-50	1-250	150-250	<0.005	70-90	10-15	9	150/200-300/900	100/200/300-500/600
Flow Batt.	1-25+	100+	16-60	0.001	60-85	5-15	9	300/600-500/1500	150/400-750/1000
Li-ion Batt.[b]	1-50+	1-200+	200-735	<0.005	92-96	5-20	9	-	170-710

a. Traditional CAES systems use fossil fuels in the process, being a hybrid between a gas turbine and a storage plant. The last presents a challenge when comparing CAES to other storage technologies. See values of the fossil fuel-free technology alternative, the Adiabatic CAES (ACAES).

b. Li-on batteries' information was obtained from Ref. [1].

2.2 Electricity Markets

ESS obtain their revenue by participating in electricity markets. Europe has a liberalized electricity system in which electricity is traded in a series of sequential markets. The first and earlier market is the forward market, which is based on bilateral contracts which can occur in a timeframe of years and continue up until one day before delivery. One day before delivery and until minutes before real-time, trading is held in centrally organized short-term markets, namely the Day Ahead (DA) and the Intraday (ID) markets. During the real time (RT), the Transmission System Operator (TSO) is responsible of maintaining the system balance via balancing and ancillary services markets [17], [18].

ESS normally participate in the short-term markets since the duration of their cycle is on the hourly magnitude. The following sections will further describe the general functioning of the different short-term markets in the Central Western European (CWE) region (i.e., Belgium, France, Germany, and the Netherlands).

2.2.1 Day Ahead Markets

The DA market is harmonized across the CWE region and is a double-sided blind auction in which market participants submit quantity-price bids on hourly basis. The demand bids indicate the quantity wanted and the highest price a buyer is willing to pay, while the supply bids represent the quantity offered and the lowest price at which a seller is willing to sell. Market players can place their bids until the DA market closure, which is at 12:00pm of the day before the delivery day (D-1) in the CWE region.

All supply and demand bids are then aggregated and matched for each hour of the day. The intersection between these two determines the market clearing volume and price [17], [19], see Figure 1.

Figure 1. Market clearing price and volume of the electricity auctions [19]

In Europe, the DA market is coupled for 25 interconnected countries. For this, all the different region's bids are run in the same market-clearing algorithm (EUPHEMIA) which allocates interconnection capacity in a way that maximizes SEW [20]. However, due to the limited interconnection capacity, DA prices can be different for each market zone when interconnection lines are congested. The electricity price of each market zone is known as Locational Marginal Price (LMP).

2.2.2 Intraday Markets

ID markets occur on the delivery day and are the last opportunity for market players to adjust their positions from the DA market. The Belgian, Dutch, and French ID markets are based on a continuous trading of one-hour products, while the German market also offers quarter-hourly products, where supply and demand bids are submitted to a central platform and matching bids are continuously cleared on an individual basis. This can be done up until five minutes before RT for Belgium and the Netherlands, and 30 minutes for Germany and France. Unlike, the DA market, with this mechanism there can be different prices for each trade. In addition to the continuous trading, the German ID market also has a discreate auction mechanism, based on principles similar to the DA market [17].

2.2.3 RT Balancing Markets

After the ID market closes, the remaining supply and demand mismatches resulting from unexpected circumstances are balanced in the RT markets, which are coordinated by the local TSO. The last has to be done to maintain the system operating within its physical constraints (i.e., frequency and voltage), in order to ensure its reliability and prevent blackouts. In this mechanism, the TSO calculates the system imbalance, net quarter-hourly difference between the total injections and offtakes, and activates the reserves as needed. The TSO then applies the corresponding imbalance pricing to the Balance Responsible Parties (BRP)[1] [17], [21].

Reserve capacity is divided into three groups: Frequency containment reserve (FCR) or primary control, automatic Frequency restoration reserve (aFRR) or secondary control, and manual Frequency restoration reserve (mFRR) or tertiary control. FCR is paid a reservation price and aFRR and mFRR a reservation and activation price.

2.3 Electricity Storage in Electricity Markets

As discussed in the literature [6], [22]–[24], ESS can participate in the DA, ID, and balancing markets, sometimes simultaneously. Additionally, storage can provide ancillary services such as peak capacity, black start services, and voltage control. It is by stacking the revenues from the participation in this different markets and service provision, that the energy storage business case becomes attractive for investors.

Even though the participation of different markets is possible and relevant, this thesis work focuses on the ESS' participation by energy arbitrage in the DA market. Energy arbitrage is the process by which the storage device is charged (i.e. energy is bought) when the energy price is low and subsequently discharged (i.e. energy is sold) when energy prices are high [23].

2.3.1 Barriers for ESS participation

It is generally agreed in the literature that one of the main barriers for the widespread deployment of energy storage is the lack of market and regulatory mechanisms that allow to monetize and capture the value of the different services that energy storage can provide, and therefore provide a

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[1] The BRP is a designated producer, major customer, energy supplier or trader responsible of taking all reasonable measures to maintain the balance between injections, offtakes, and commercial power trades within their portfolio. Each grid access point has a designated BRP [63].

positive business case for owners. These barriers are related to each country's electricity market structure and regulation, so their effect vary in a case-by-case basis [6], [14], [18], [23].

The European Commission has carried out three reports in which they explored the role of energy storage in the European Union as well as the main challenges for its deployment [25]–[27]. In these, they have identified some regulatory issues that affect the participation of energy storage in the electricity markets and hamper the profitability of storage investments. Some of the main issues are:

- Lack of a market definition of storage and specific participation rules.
- Lack of appropriate bid formats (to place simultaneously market orders for the charge and discharge phases).
- Market entry and participation barriers in capacity mechanisms (i.e., minimum capacities, derating factors, unsuitable contracting window).
- Limited opportunity for participation in ancillary service provision, especially for non-frequency services (either because of market entry and participation restrictions for storage or because these are not-market based).
- Double grid tariffs charging and double taxation (as generator and consumer) as a result of storage not being specified in the regulatory framework.
- Requirements for legal unbundling restrict energy storage ownership by TSO, and therefore to capture the value of storage's transmission and distribution services.

For the case of Belgium, no major entry or participation barriers for the DA and ID markets were found in literature. Starting in 2020, storage can also participate in capacity mechanisms, including through aggregation. Regarding ancillary services, storage is allowed to provide FCR and PHES is allowed to provide aFRR. Energy storage in Belgium still faces the challenge of paying double grid tariffs and taxation as well as the ownership restriction [28]–[30].

2.4 Literature Review

There is a vast amount of existing research regarding energy arbitrage with ESS. Several research works have explored the optimal ESS size and operation to maximize the owner's arbitrage revenues in various markets such as the Australian [15], Italian [14], German [31], and the American [24],[25]. The studies assume different market structures and storage technologies and characteristics (i.e., duration, efficiency, capacity, etc.). While the resulting optimal ESS size and operation may differ according to the case studied, there is a widespread agreement that energy storage is not currently profitable if energy arbitrage in wholesale short-term electricity markets is considered the only source of revenue. However, economic feasibility of ESS can be reached by stacking the revenue of providing different services [23]. It has been found that the inclusion of the participation in the balancing market and the provision of frequency reserves can considerably improve the business case of ESS [22] .

There are two important assumptions to consider when analysing electricity storage for energy arbitrage, the first is the perfect vs. imperfect foresight and the second one is price-taker vs. price-maker. In a perfect foresight approach, the analysis assumes that the operator knows with certainty the future hourly prices of the market and therefore can capture the whole value of the price differences by the optimal scheduling of the storage operation. This assumption can lead to high or unrealistic profits for ESS [22]. The second assumption relates to if it considered that the ESS operation can affect the market clearing prices, i.e., price-maker, or not, i.e., price-taker. Most authors use the price-taker approach justifying that the ESS is too small to affect the market prices [7], [15], [22], [32] . However, the last might not apply when studying large-scale ESS or aggregated effects of ESS operation [7], [32].

Some studies [7], [8], [24] have researched the effect of large-scale energy storage in the wholesale electricity market, finding that the inclusion of large-scale energy storage for arbitrage purposes results in lower prices on-peak hours and higher prices off-peak hours, reducing the value that can be obtained from arbitrage. In consequence, Ref. [24] found that considering the price-effect of ESS leads to three changes in the storage operation and trading behaviour: fewer full load hours, more operational hours, and less traded energy.

Even though extensive research has been carried out in relation to the value of energy storage for energy arbitrage applications, this has mostly been from the owner's perspective. There is less literature quantifying the value of storage from a societal perspective.

Nyamdash Et. Al. [11] explored the social effect of a 5 hour PHES in the 2009 Irish Single Electricity Market using a unit commitment model and econometric techniques. The research found that the deployment of a storage system reduces the system's production costs but increases the average electricity price. However, the reduction in the production cost was found to be less than the increase in the consumer's cost of electricity resulting in a net increase in costs due to storage, and a negative social effect from storage.

Contrastingly, Sioshansi Et. Al. [8] found that energy storage leads to an increased SEW when analysing the welfare effects of large-scale energy storage in the PJM region in the United States. For this they first calculated the off-peak and off-peak price with and without storage (for a storage duration of 4, 8 and 16 hours) using an econometrically estimated nondecreasing function of the net power demand including storage output, aggregated over the whole network. The research found that storage can lead to a large shift in producer and consumer surplus, generally increasing consumer surplus and reducing generators surplus. However, the former resulted larger than the later, resulting in an overall increased SEW with the inclusion of large-scale storage.

Other research studied the effect of ESS in SEW under different market structures. Sioshansi [9] found that merchant ownership of storage is welfare-maximizing compared to the alternatives of consumer or generator ownership. Ownership by a municipality, cooperative, or integrated utility was not included in the analysis. This aligns with the results found by Cerezo Et. Al. [10] which, by studying the effect of market power, concluded that the worst outcome for consumers and total welfare occurs under a vertical integration, where a vertically integrated firm has market power in both storage and generation. While the aforementioned research studied SEW with ESS private ownership, He Et. Al. [12] explored the consequences of public ownership, concluding that the public operation of ESS leads to higher SEW than the private operation.

Most of the research found regarding the impact of large-scale ESS in SEW was carried out between the years 2009 and 2014. Since then, the role of VRES in electricity generation has increased and it is expected to continue increasing [6]. The growing penetration of VRES in the power system also leads to changes in the wholesale electricity market, generally reducing market-clearing prices and the generator's profits [13]. The present study assessed how merchant owned large-scale ESS affects the SEW in the present and future DA wholesale electricity markets by studying its effect under different VRES penetration and storage capacity levels. Furthermore, most of the storage SEW studies have been carried out using econometric market functions or published market resilience functions to calculate the price and SEW effects of large-scale ESS. However, since said functions are derived based on specific market conditions, this technique cannot be used to assess different generation mixes and VRES penetration levels. Therefore, an important part of the current research work was to develop a model that allows to integrate the price-maker operation of large-scale ESS into the DA market under different generation conditions.

The study was done based on the Belgian DA market case, considering that the added storage capacity has the technical characteristics of a BESS. This storage technology was chosen because the world's BESS capacity is expected to see a considerable increase during the following years due to the lowering prices and multiple services that it can provide [1], [34]. On the other hand, the technologies typically used for this kind of assessments, PHES and CAES, have been widely studied and can only have a limited growth due to the geographic conditions needed. However, given that BESS tend to be of a smaller capacity than PHES, with the largest BESS project currently planned being of 1,200 MWh and 300 MW [35], multiple smaller BESS were considered for the addition of storage capacity for the modelling.

To the best of the author's knowledge, a SEW analysis has not been carried out for the addition of multiple merchant-owned large-scale BESS in the DA Belgian market.

3 Methodology

In order to answer the research question, the present study developed a model to incorporate merchant-owned large-scale ESS into the DA wholesale electricity market. To achieve the previous, two perspectives had to be considered: the ESS player´s and the Market Operator´s. Subsequently, data from the Belgian electricity system was used to run the resulting model for scenarios with varying VRES shares in electricity generation and ESS installed capacity. The difference in the resulting SEW and shifts in consumer and producer surplus were then analysed to conclude on the potential social impacts of large-scale ESS integration in the present and future electricity markets.

3.1 Market Clearing and ESS Operation Model

The DA wholesale electricity market can be formulated as a linear optimization model in which SEW, the overall benefit that arises from trading [36], is maximised under a set of economic and technical constraints. In this step, a basic version of the DA market clearing problem programmed in Julia language and provided by Utrecht University was used as a reference and starting point for the market-based analysis of the integration of large-scale ESS. It is worth noting that the integrated model has two important elements: the Marker Clearing, carried out by the market operator, and the ESS bidding strategy, carried out by the ESS players.

3.1.1 Market Clearing Optimization Model

The reference market clearing model is seen from the perspective of the market operator who aims to maximize the total SEW of the system in T hours. The problem was formulated as a power exchange in which market participants submit their bids and no information about their production costs is known by the market operator. The mathematical formulation of the objective function can be seen in Equation 1a.

$$\max_{Qd_{d,t},Qs_{s,t},\,Qdis_{n},Qch_{n},\delta_{k,t}} \sum_{t\in T}\left(\sum_{d\in D}\left(Pd_{d,t} * Qd_{d,t}\right) - \sum_{s\in S}\left(Ps_{s,t} * Qs_{s,t}\right) - \sum_{n\in N}\left(Odis_{n,t}\cdot Qdis_{n,t}\right) + \sum_{n\in N}\left(Och_{n,t}\cdot Qch_{n,t}\right)\right) \tag{1a}$$

where $Qs_{s,t}$ and $Qd_{d,t}$, are the decision variables corresponding to the dispatched generation and accepted demand, respectively, of a market player d or s corresponding to the hour t. Likewise, $Q_{dis_{n,t}}$ and $Q_{ch_{n,t}}$ represent the discharged or charged energy, respectively, for ESS player n at hour t. Moreover, $\delta_{k,t}$ are the decision variables corresponding to the voltage angles of node k at hour t.

The optimization problem is subject to the constraints represented by the equations 1b to 1j.

$$s.t:$$

$$\sum_{d\in\varphi_k^d} Qd_{d,t} - \sum_{s\in\varphi_k^s} Qs_{s,t} - \sum_{l\in\varphi_k^l} B_{k,l}\left(\delta_{k,t}-\delta_{l,t}\right) = 0 \qquad \forall k,\forall t \;;\boldsymbol{\lambda_{k,t}} \tag{1b}$$

$$Qs_{s,t} \le Msk_{s,t} \qquad \forall s,\forall t \tag{1c}$$

$$Qd_{d,t} \le Mdk_{d,t} \qquad \forall d,\forall t \tag{1d}$$

$$Qdis_{n,t} \le Pdis_{n,t} \qquad \forall n,\forall t \tag{1e}$$

$$Qch_{n,t} \le Pch_{n,t} \qquad \forall n,\forall t \tag{1f}$$

$$-TrC_{k,l} - \beta_{k,l}\left(\delta_{k,t}-\delta_{l,t}\right) \le 0 \qquad \forall k,\forall l\in\varphi_k^l,\forall t \tag{1g}$$

$$\beta_{k,l}\left(\delta_{k,t}-\delta_{l,t}\right) - TrC_{k,l} \le 0 \qquad \forall k,\forall l\in\varphi_k^l,\forall t \tag{1h}$$

$$\delta_{k=ref,t} = 0 \qquad \forall t \tag{1i}$$

$$-Qs_{s,t}, -Qd_{d,t} \le 0 \qquad \forall s,\forall d,\forall t \tag{1j}$$

Equation 1b corresponds to energy balance constraint at each node. Equations 1c to 1f correspond to the maximum demand, generation, and storage bid boundary constraints. Equations 1g to 1h ensure that the capacity of each transmission line is not exceed and define the reference node. Lastly, Equation 1j represents the non-negativity constraints of the decision variables $Qd_{d,k,t}\ and\ Qs_{s,k,t}$. The explanation of the different variables and parameters used in Equations 1a to 1j can be found in Table 2.

Table 2. Variables and parameters of market optimization formulation

Symbol	Explanation
Decision variables	
$\boldsymbol{Qd_{d,t}}$	Accepted demand player d at hour t.
$\boldsymbol{Qs_{s,t}}$	Dispatched generation player s at hour t
$\boldsymbol{Qdis_{n,t}}$	Accepted supply (discharging energy) for ESS player n at hour t.
$\boldsymbol{Qch_{n,t}}$	Accepted demand (charging energy) for ESS player n at hour t.
$\boldsymbol{\delta_{k,t}}$	Voltage angle node k at hour t
Parameters	
$\boldsymbol{Pd_{d,k,t}}$	Willingness to pay demand d in node k at hour t (price in bid)
$\boldsymbol{Ps_{s,k,t}}$	Price in bid generator s at node k at hour t
$\boldsymbol{O_{dis_t}}$	Discharge price bid of ESS at time t
$\boldsymbol{O_{ch_t}}$	Charge price bid of ESS at time t
$\boldsymbol{Mdk_{d,k,t}}$	Max demand of demand s at node k at hour t (quantity in bid)
$\boldsymbol{Msk_{s,k,t}}$	Max generation generator s at node k at hour t (quantity in bid)
$\boldsymbol{P_{dis_t}}$	Discharging Rate [MW] – Submitted as discharging quantity bid for time t
$\boldsymbol{P_{ch_t}}$	Charging rate [MW]- Submitted as charging quantity bid for time t
$\boldsymbol{\beta_{k,l}}$	Susceptance transmission line between nodes k and l
$\boldsymbol{TrC_{k,l}}$	Max transmission capacity between nodes k and l
Dual variables	
$\boldsymbol{\lambda_{k,t}}$	Nodal electricity market clearing price (MCP) in node k at hour t

3.1.2 Energy Storage Systems Bidding Strategy

The inclusion of large-scale ESS participating in energy arbitrage in the market clearing optimization formulation had two main challenges. The first one is that ESS can act as both generator and consumer. The second one is that the ESS's operation and bidding strategy depend on electricity market prices. ESS charge when the price is low and discharge when it is high. At the same time, this market-clearing price is determined based on the demand and generation bids, which includes the energy storage participation. To simulate the bidding strategy of the ESS player, two optimization problems were implemented. First, an optimization problem for the operation of a price-taker ESS was built and integrated in the market clearing problem. Once this was functional, the model was improved, by replacing the price-taker ESS approach with a price-maker strategy.

3.1.2.1 Price-Taker

In the price-taker approach considered first, the ESS player assumes that its market share is small enough to not impact the MCPs. Therefore, the bidding strategy does not consider the potential effects of the storage operation on these, simplifying the analysis.

For these approach, historical MCPs were used as an input to determine the storage optimal scheduling and obtain the charging and discharging bids. Subsequently, the market-clearing optimization was run including the storage bids obtained in the previous step, resulting in the MCP and quantities with storage. Figure 2 illustrates the modelling steps for the price-taker approach.

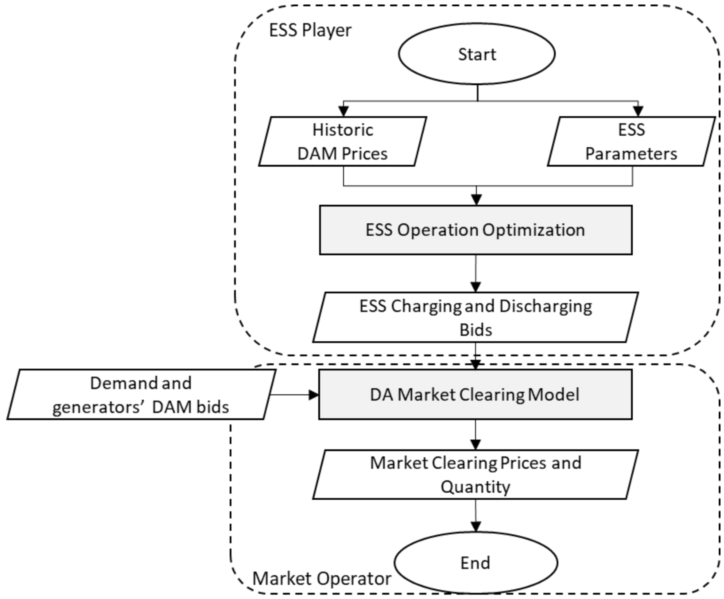


Figure 2. Modelling approach for price-taker ESS inclusion in DA market-clearing problem.

The ESS bids were generated using an optimization model programmed in Julia language, shown as the "ESS Operation Optimization" process in Figure 2. The objective of the optimization problem is to maximize the ESS's operation profits throughout the modelled day. This profit is calculated as the difference of the revenues from selling the discharged energy and the purchasing costs of the charged energy, as shown in Equation 2a [7], [15], [31].

$$\max_{E,b,P_{ch},P_{dis}} \sum_{t=1}^{24} Price_t \left(P_{dis_t} - P_{ch_t}\right) \cdot \Delta t \qquad (2a)$$

Where $Price_t$ is the historical DA market marginal price at time t, P_{dis_t} is the discharged power, P_{ch_t} is the charged power, and Δt the length of the time steps, which are of one hour. Note that additional operational costs besides the charging costs are not included in the analysis for simplification purposes.

The problem is restricted to the constraints shown in Equations 2b to 2f.

$$E_{t+1} = E_t + (\eta_{ch_t} \cdot P_{ch_t} - \eta_{dis}/P_{dis_t}) \cdot \Delta t \qquad \forall t \qquad (2b)$$

$$E_r \cdot (1 - DoD) \leq E_t \leq E_r \qquad \forall t \qquad (2c)$$

$$E_1 = E_r \cdot SOC_0 \qquad \forall t \qquad (2d)$$

$$P_{dis_t} \leq b_t P_r \qquad \forall t \qquad (2e)$$

$$P_{ch_t} \leq (1 - b_t) P_r \qquad \forall t \qquad (2f)$$

Equation 2b ensures the energy balance in the storage system, where the energy storage in a certain time has to be equal to the one of the previous time step, plus/minus the charged/discharged energy, considering the losses due to the system charging and discharging efficiency [7]. Equation 2c limits the energy storage at any time to the system rated energy storage in the upper bound and to the energy level at the recommended depth of discharge (DoD) in the lower bound. Equation 2d is used to set the initial ESS' State of Charge (SOC). Equations 2e and 2f, limit the charging and discharging power to be lower or equal to the system's rated power. Additionally, the inclusion of the binary variable b_t restricts the storage operation to avoid simultaneous charging and discharging. The explanation of the different variables and parameters used in Equations 2a to 2d can be found in Table 3.

Table 3. Variables and parameters of the ESS operation optimization formulation

Symbol	Explanation
Decision variables	
$\boldsymbol{E_t}$	Energy Stored [MWh]
$\boldsymbol{P_{dis_t}}$	Discharging Rate [MW] – Submitted as discharging quantity bid for time t
$\boldsymbol{P_{ch_t}}$	Charging rate [MW]- Submitted as charging quantity bid for time t
$\boldsymbol{b_t}$	Binary variable to represent charging (b=0) or discharging (b=1)
Parameters	
$\boldsymbol{Price_t}$	DA Reference Market Clearing Price [€/MWh]
$\boldsymbol{P_r}$	Rated active power [MW]
$\boldsymbol{E_r}$	Rated Energy Storage [MWh]
$\boldsymbol{SOC_0}$	Initial State of Charge [%]
$\boldsymbol{DoD}$	Recommended depth of Discharge [%]
$\boldsymbol{\eta_{ch}}$	Charging Efficiency [ratio]
$\boldsymbol{\eta_{dis}}$	Discharging Efficiency [ratio]
$\boldsymbol{\Delta t}$	Difference between time periods [hours]

The described optimization model is applicable to most energy storage systems, the differences between these can be captured by the input parameters. However, in the case of battery storage, battery degradation also plays a part in the considerations of daily system operations [31]. Battery degradation was not included in the present model due to the short modelling periods (24 hours).

3.1.2.2 Price-Maker

In the price-maker approach, the ESS player assumes that its bid can affect the market clearing price by changing the bided quantity, exerting market power and becoming a strategic player. The bids of strategic players in the electricity markets can be optimized based on a Stackelberg game. Stackelberg games are hierarchical games involving a leader, that acts first, and a follower, that acts second. In these, the leader's profit is affected by the follower's reaction to his action. However, the leader's action also influences the follower's profit. Therefore, the leader must consider the followers optimal reaction when optimizing his strategy [37], [38].

As shown in Figure 3, the strategic player (i.e., ESS) is the leader in this case, deciding how much quantity to bid, either as a supplier or a demand, and at which price based on the objective of maximizing its profit, which is a function of the MCP. The market operator would then be the follower, clearing the market for all the submitted bids, including the ones from the strategic player, to obtain the dispatch quantities and MCP.

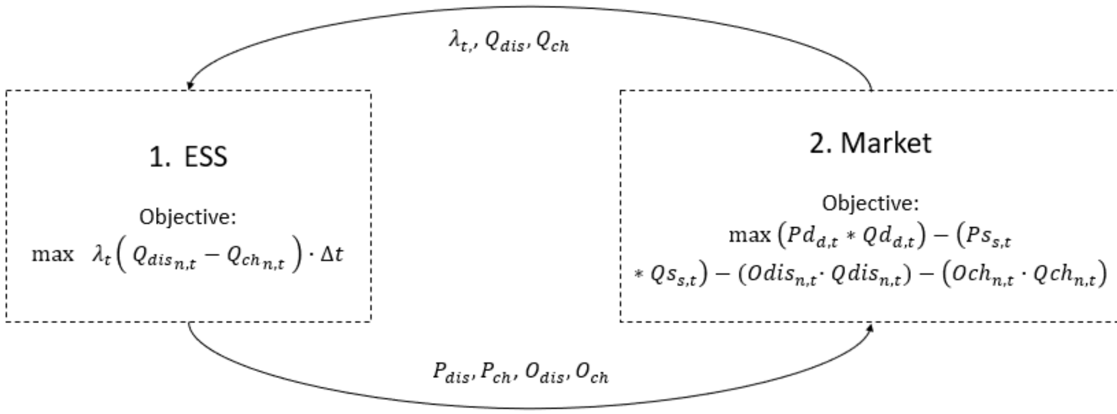


Figure 3. Stackelberg game for ESS as strategic player

The described Stackelberg game can be formulated combining the market clearing and ESS operation optimization problems described in the previous sections (Equations 1a to 1j and 2a to 2f) in a bilevel optimization problem. In this formulation, the lower level problem is added as a constraint to the upper level problem, as shown in Equations 3a to 3u [38]. Note that P_{dis}, P_{ch}, O_{dis}, and O_{ch} are given by the ESS player, therefore they represent decision variables in the upper-level problem but parameters in the lower-level problem. On the other side, Q_{dis}, Q_{ch}, and λ_t are a result of the decisions of the market operator, therefore they are parameters in the upper-level problem, but decision variables in the lower-level problem.

While the storage price bids, $O_{dis_{n,t}}$ and $O_{ch_{n,t}}$, could also be obtained from the ESS bidding strategy optimization problem, in this case they were set to 0€/MWh for charging and 3000 €/MWh (the DA price cap in the CWE region) for discharging. This was assumed to ensure that the bided quantity gets cleared by the market, so the ESS has enough energy capacity to fulfil the charging or discharging offers in the next time periods. In the real DA market, the previous could be achieved with the use of block bids.

Upper-Level Problem: Maximization of profit storage player

$$\max_{E, b, P_{dis_t}, P_{ch_t}, O_{dis_t}, O_{ch}} \quad \sum_{t=1}^{24} \sum_{n \in N} \lambda_{k,t} \left(Q_{dis_{n,t}} - Q_{ch_{n,t}} \right) \cdot \Delta t \qquad (3a)$$

s.t.

$$E_{n,t} = E_{n,t-1} + \left(\eta_{ch_n} \cdot Q_{ch_{n,t-1}} - \eta_{dis_n} / Q_{dis_{n,t-1}}\right) \cdot \Delta t \qquad \forall t, \forall n \qquad (3b)$$

$$E_{r_n} \cdot (1 - DoD_n) \le E_{n,t} \le E_{r_n} \qquad \forall t, \forall n \qquad (3c)$$

$$E_{n,1} = E_{r_n} \cdot SOC_{0_n} \qquad \forall t, \forall n \qquad (3d)$$

$$0 \le P_{dis_{n,t}} \le b_{n,t} P_{r_n} \qquad \forall t, \forall n \qquad (3e)$$

$$0 \le P_{ch_{n,t}} \le (1 - b_{n,t}) P_{r_n} \qquad \forall t, \forall n \qquad (3f)$$

$$O_{ch_{n,t}} = 3000 \cdot (1 - b_{n,t}) \qquad \forall t, \forall n \qquad (3g)$$

$$O_{dis_{n,t}} = 0 \cdot b_{n,t} \cdot P_{r_n} \qquad \forall t, \forall n \qquad (3h)$$

Lower-Level Problem: Market Clearing

$$\max_{Qd_d, Qs_s, Qdis_n, Qch_n\, \delta_k} \sum_{t\in T}\Big(\sum_{d\in D}\big(Pd_{d,t} * Qd_{d,t}\big) - \sum_{s\in S}\big(Ps_{s,t} * Qs_{s,t}\big) - \sum_{n\in N}\big(Odis_{n,t} \cdot Qdis_{n,t}\big) + \sum_{n\in N}\big(Och_{n,t} \cdot Qch_{n,t}\big)\Big) \qquad (3i)$$

s.t.

$$\sum_{d\in\varphi_k^d} Qd_{d,t} - \sum_{s\in\varphi_k^s} Qs_{s,t} - \sum_{n\in\varphi_k^n} Qdis_{n,t} + \sum_{n\in\varphi_k^n} Qch_{n,t} - \sum_{l\in\varphi_k^l} B_{k,l}\big(\delta_{k,t} - \delta_{l,t}\big) = 0 \qquad \forall k, \forall\, t; \boldsymbol{\lambda_{k,t}} \qquad (3j)$$

$$Qs_{s,t} \le Msk_{s,t} \qquad \forall s, \forall t \qquad (3k)$$

$$Qd_{d,t} \le Mdk_{d,t} \qquad \forall d, \forall t \qquad (3l)$$

$$Qdis_{n,t} \le Pdis_{n,t} \qquad \forall n, \forall t \qquad (3m)$$

$$Qch_{n,t} \le Pch_{n,t} \qquad \forall n, \forall t \qquad (3n)$$

$$-TrC_{k,l} - \beta_{k,l}\big(\delta_{k,t} - \delta_{l,t}\big) \le 0 \qquad \forall k, \forall l \in \varphi_k^l, \forall t \qquad (3o)$$

$$\beta_{k,l}\big(\delta_{k,t} - \delta_{l,t}\big) - TrC_{k,l} \le 0 \qquad \forall k, \forall l \in \varphi_k^l, \forall t \qquad (3p)$$

$$\delta_{k=ref,t} = 0 \qquad \forall t \qquad (3q)$$

$$Qs_{s,t} \ge 0 \qquad \forall s, \forall t \qquad (3r)$$

$$Qd_{d,t} \ge 0 \qquad \forall d, \forall t \qquad (3s)$$

$$Qdis_{n,t} \ge 0 \qquad \forall n, \forall t \qquad (3t)$$

$$Qch_{n,t} \ge 0 \qquad \forall n, \forall t \qquad (3u)$$

Given that the available options to solve bilevel optimization problems in Julia are limited, the price-maker ESS scheduling problem had to be reformulated as a Mixed-integer linear programming (MILP) problem that could be solved with most of the available solvers in Julia. To achieve this, first, the bilevel problem was reduced to a single level constrained optimization problem by reformulating the lower-level problem using the Karush-Kuhn-Tucker (KKT) conditions, and adding them as a constraint to the upper-level problem [38], [39]. To derive the KKT conditions, the lower-level problem was reformulated in the standard optimisation form to obtain the Lagrangian function by applying the equations shown in Figure 4. The previous resulted in a Mathematical Program with Complementarity Constraints (MPCC). The complementary conditions were then linearized using the Fortuny-Amat approach, which achieves this by including a large constant "M" and auxiliary binary variables [40], resulting in a Mixed Integer Non Linear Program (MINLP). The non-linearity in the problem arises from the multiplication of two decision variables in the objective function (λ and Q_{dis}, Q_{ch}), resulting in bilinear terms. Finally, the strong duality equality of the lower-level's problem and the KKT conditions were used to substitute the bilinear terms, obtaining a MILP which was solved using Julia's JuMP solver and the GLPK Optimizer [41]. The complete mathematical formulation, showing all the described steps, can be found in Appendix A.

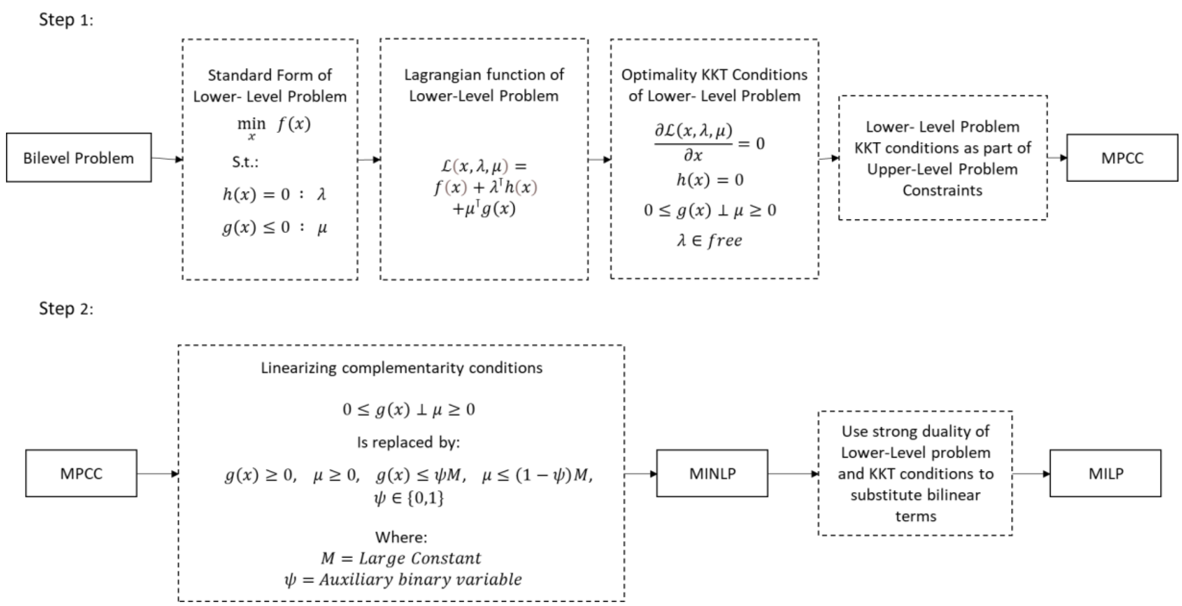


Figure 4. Steps for transformation from Bilevel Problem to MILP for programming in Julia. f(x) represents the objective function, h(x) the equality constraints, and g(x) the inequality constraints, λ is the dual variable of the equality constraints and, μ is the dual variable of the inequality constraints.

The modelled scenarios, described in Section 3.2, contain multiple ESS owned by different market participants. Therefore, assumptions had to be made regarding their interaction and strategy when analysing the price-maker approach. To avoid adding further complexity to the model and obtain a problem that could be solved with standard computing power, it was assumed that each ESS applies a strategy known as Level-1 thinking in game theory, which is part of the Level-k approach. In this strategy, the player assumes that all other participants have less sophisticated strategies than his (Level-k) or behave in a non-strategic way (Level-1) [42]. In this case that means that each ESS optimizes its price-maker strategy considering that the other storage participants will behave like price-takers. The price-maker optimal operation of each ESS was therefore calculated by adding the estimated price-taker supply and demand bids of other ESS to the market clearing in the bilevel problem from Equation 3. Once the Level-1 price-maker operation of all ESS were simulated, the obtained bids were assigned as input for the market clearing program, obtaining the marginal clearing prices and dispatched quantities. Figure 5, shows the described approach. This process was done for each modelling scenario.

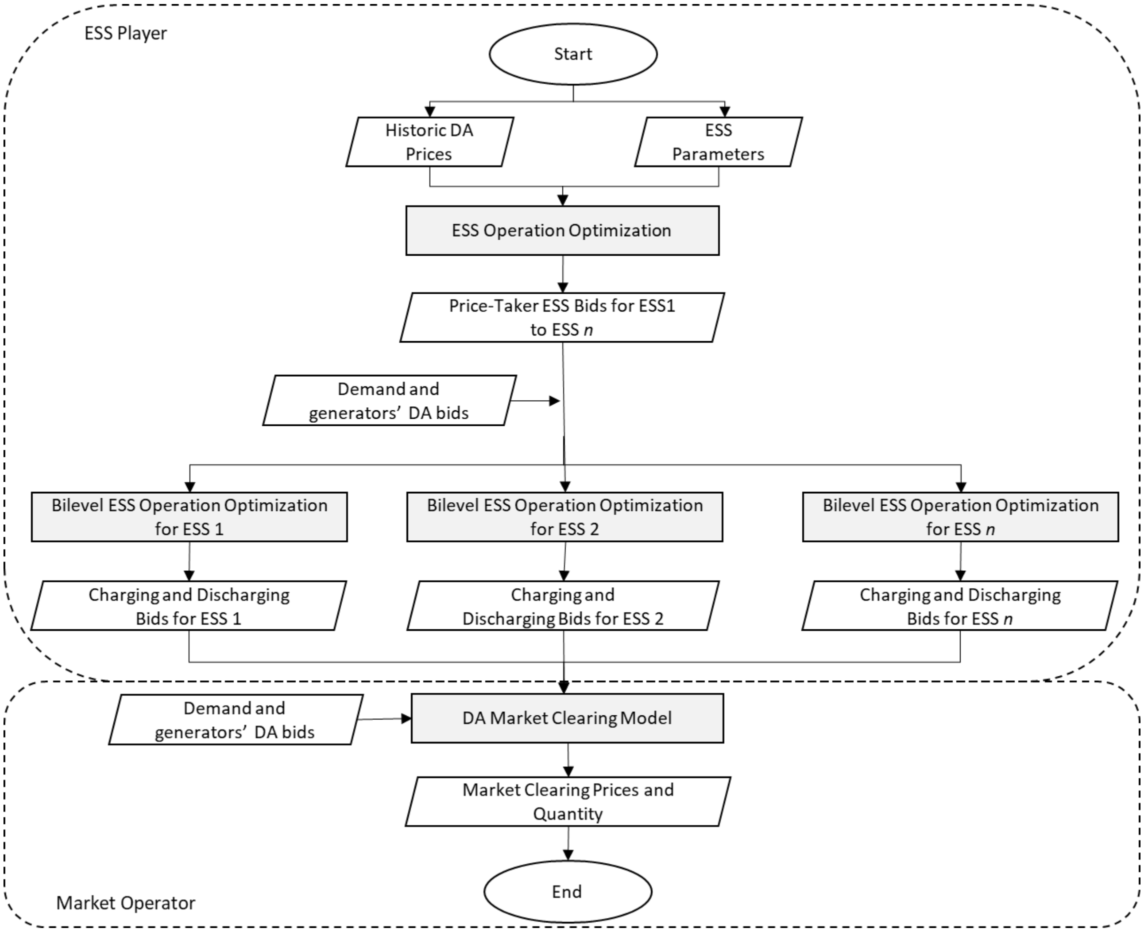


Figure 5. Modelling approach for multiple price-maker ESS inclusion in DA market-clearing problem.

When running the program, it was seen that solving the resulting Bilevel ESS Operation Optimization was computationally expensive and had long running times. Further, the optimal solution for the operation of certain ESS in certain scenarios had not been reached by the GLPK solver after 12 hours, while most of the other optimal values were reached in under an hour. Therefore, a time limit of 90 minutes was set per optimization problem to allow the running of all scenarios within the time frame and computational power limitations of the research work. When the time limit was reached, the program corroborated if the solver had found an approximation to the optimal solution, even though this was still suboptimal. If so, said values were used for the operation of that specific ESS. If no values, even suboptimal ones, had been found within the time limit, it was then assumed that the solver had not found any feasible solution for the ESS to operate in a revenue maximizing way, and was therefore assumed to remain non-operational in the specific modelling day and scenario. The result section indicates when suboptimal values were used.

3.2 Scenarios Construction

The model explained in the previous sections was run for scenarios with varying VRES and storage levels. For each scenario, a 24-hour period was modelled for representative days of the year 2019. The representative days are non-holiday weekdays, selected in such a way to consider seasonal changes in demand and VRES generation. Table 4 shows the selected representative days and their characteristics, while Figure 6 shows the demand and VRES capacity factors values for the selected dates.

Table 4. Selected Modelling days

Date	Name	Comment
Tuesday, 15th January 2019	January	High Demand, Intermediate Wind, Low Solar
Tuesday, 12th March 2019	Mach	Intermediate Demand, High Wind, Intermediate Solar
Tuesday, 18th June 2019	June	Low Demand, Low Wind, High Solar
Tuesday, 17th September 2019	September	Low Demand, Low Wind, Intermediate Solar

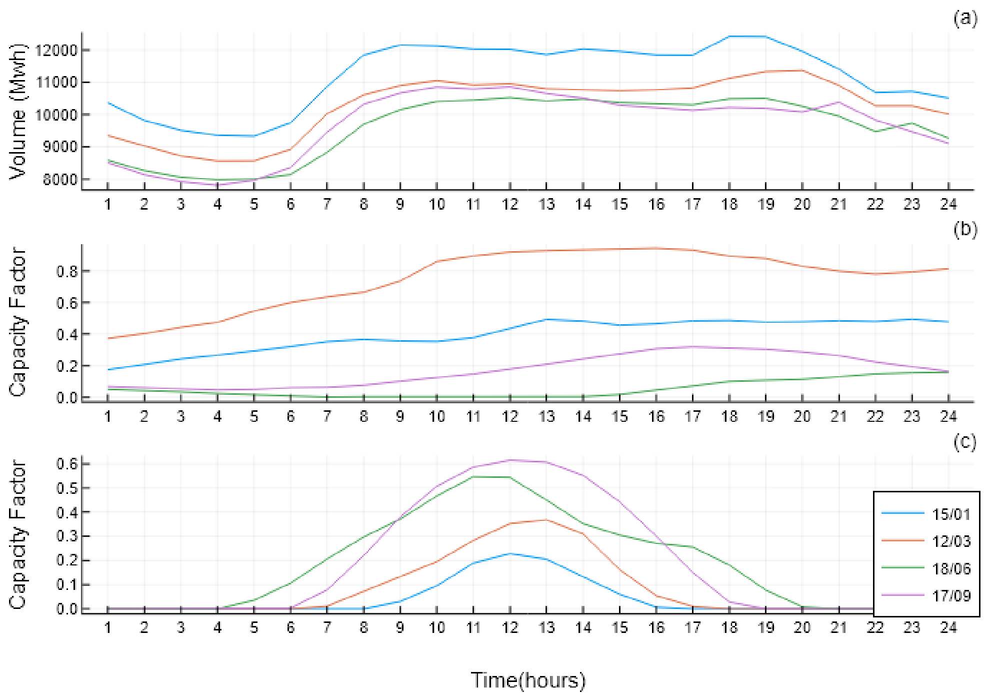


Figure 6. Characteristics of selected dates: (a) Demand, (b) Wind generation, (c) Solar generation.

Table 5 summarizes the scenarios used in the analysis. First a Baseline scenario was used to assess the large-scale ESS SEW effects given the 2019energy mix. Subsequently, the generation mix was changed to represent a higher penetration of VRES as expected in 2030. The comparison between both scenarios provides an indication of the SEW effects of large ESS in future energy systems and their role in the energy transition. Additionally, five storage levels were included for each generation mix in order to study the social benefits of additional storage capacity and storage market players. More information about each scenario can be found in the following sections.

Table 5. Modelling scenarios description.

Scenario name	VRES Penetration	Storage/No Storage	Storage Level
Baseline No Storage	Low (current)	No Storage	-
Baseline Existing PHES		Existing PHES	Current
Baseline Low		BESS Storage	Low
Baseline Medium			Medium
Baseline High			High
LVRES No Storage	High	No Storage	-
LVRES Existing PHES		Existing PHES	Current
LVRES Low		BESS Storage	Low
LVRES Medium			Medium
LVRES High			High

3.2.1 Baseline scenarios

The Baseline scenarios were based on the Belgian power system in 2019. The hourly simulations assumed that all the energy is sold and bought in the DA market, therefore no long-term, ID, or RT markets are included in the model.

Supply was modelled according to the Belgian Production Park in 2019, as registered by Elia, the Belgian TSO [43]. For simplification purposes, a perfectly competitive market was considered, where the supplier (generator) bid is equal to the short run marginal cost (SRMC) for producing electricity. The SRMC for each thermal generator (i) was calculated as shown in Equation 4.

$$SRMC_i = h_i(C_{fuel} + e_{CO_2} \cdot C_e) \quad (4)$$

Where h_i is average heat rate in GJ/MWh, C_{fuel} the cost of fuel in $€/GJ$, e_{CO_2} the fuel's emissions factor in $tCO_2\ /GJ$, and C_e is the tax on emissions in $€/tCO_2$. The heat rate was calculated as the inverse of the efficiency η_i, as shown in Equation 5, and it was assumed to be constant and independent of the load.

$$h_i = \frac{1 \cdot 3.6}{\eta_i} \quad \text{a(5)}$$

Efficiencies of each plant were obtained from the Joint Research Centre (JRC) Open Power Plants Database [44]. If no efficiency was found for a plant, the efficiency of another plant with a similar generation technology was used. The CO_2 emissions factors were taken from the IPCC Guidelines for National Greenhouse Gas Inventories [45] and the CO_2 tax from the average price of the European Emission Allowances (EEA) in 2019. Detailed considered information can be found in Appendix B.

The SRMC of VRES generation and hydropower was assumed to be zero due to null or neglectable fuel price and the lack of carbon taxes. Each generator is assumed to place a bid for the maximum generation capacity for each hour. For VRES generation, the bid quantity is equivalent to the installed capacity times the daily average capacity factor according to wind or radiation conditions of the modelled day [46], [47].

Due to maintenance, reparation, or unexpected issues, generation facilities are not always fully available. To take the previous into consideration, expected available generation capacity and planned and forced outages from Elia's historical data [43] were used to determine which generators were not operating or had limited capacity on the modelled days.

The total load data from Elia was used for the demand bids modelling. The energy traded in the day ahead market in Belgium represents around 26% of the total hourly load [48]. Therefore, 74% of the historical load data was modelled as an inelastic bid with a price bid of 3000 €/MWh, the price cap. The remaining 26% was divided in different demand bids, as shown in Figure 7, in order to approximate the increased elasticity of demand observed in the Belgian DA market [49].

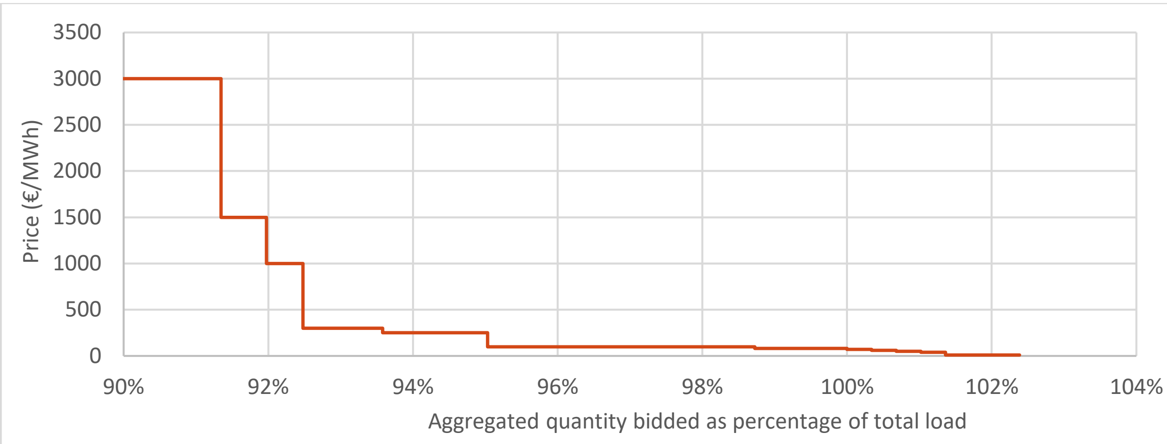


Figure 7. Modelling of aggregated demand curve based on percentage of Elia's total load.

In 2019, Belgium was directly interconnected to five bidding zones: The Netherlands (NL), France (FR), Germany/Luxembourg (DE-LU), and the United Kingdom (UK). The actual cross-border power flows of the modelled day [50] were used to model the imports and exports to or from these zones to Belgium. Each interconnected bidding zone was added to the market clearing model either as a generator or a load (depending on the direction of the flow) with a price bid of 0 or 3000 €/MWh, respectively to ensure that the bids are accepted by the market. These flows were used for all the scenarios.

Figure 8 shows the resulting supply and demand for the Belgian market with and without including the imports and exports. As it can be seen, the supply from the generators is enough to satisfy all the demand in all the modelling dates except January and a short period in June. In January the high demand combined with the planned and forced outages result in a lack of supply at the peak demand hours. The high wind availability in March leads to a high supply in relation to the demand. June and September show a peak in supply during midday and a decrease towards the night hours due to the high solar generation in said dates.

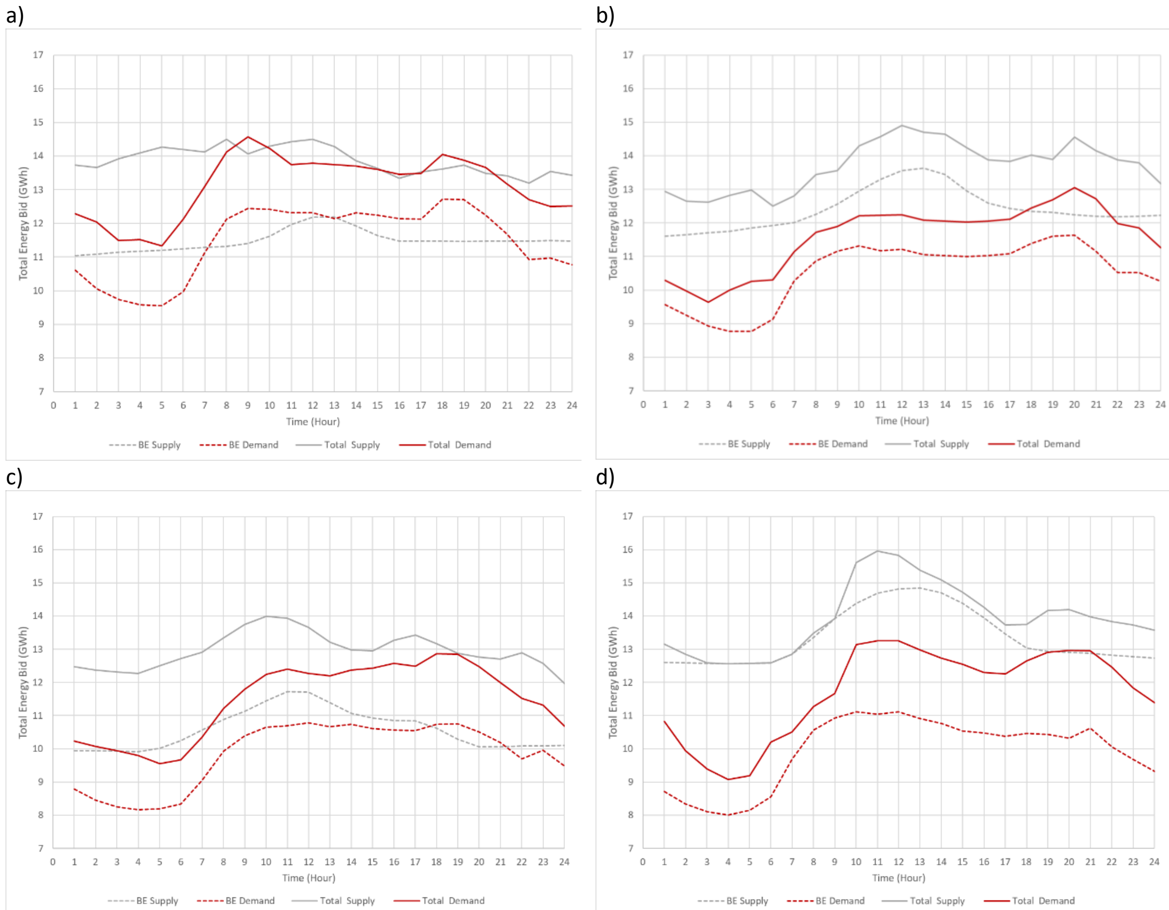


Figure 8. Belgium Supply and Demand and including imports and exports (Total Supply and Total demand) for the following modelling days: a) January, b) March, c) June and e) September.

Regarding the historical prices needed as input for the price-taker storage operation, the DA market clearing prices in Belgium for the modelled days in 2019 were used [50]. Given that the Baseline market modelling tried to replicate the supply and demand conditions of the representative days (including the operation of the existing PHES), the actual DA market clearing prices should approximate the resulting modelling prices. However, due to the impossibility to get exact market information and the presence of some assumptions (made regarding the demand elasticity, imports, exports, and marginal costs) the obtained MCPs are slightly different. The previous results in a ESS operation modelling with imperfect price foresight.

3.2.2 Large share of VRES (LVRES) scenarios

In the LVRES scenarios, the current generation mix was changed to reflect a larger share of VRES in the Belgian electricity sector. This change is expected given the European climate commitments to decarbonise the economy, reducing the greenhouse gasses emissions by at least 40%, and increasing the share of renewable energy to at least 32% of EU energy use by 2030 [51].

The new generation mix was based in the “Large Scale RES” scenario proposed by Elia for 2030 [52]. The previous considered reaching the 2030 European climate targets and added additional renewable energy generation via large-scale projects, which are mainly onshore and offshore wind power. It is also assumed that there is no nuclear capacity due to the nuclear phase-out planned for

2025. Additionally, some old natural gas-based thermal plants are decommissioned. New thermal plants are used to ensure adequacy. The used Elia study proposed the installed capacity per technology for 2030 based on the assumption that demand will increase from the 2019 levels. However, the demand from 2019 was held constant for the purpose of this study. Therefore, the installed capacity was scaled to fit the 2019 demand, maintaining the share per technology in the generation mix proposed by Elia. This was done by calculating the percentage increase in demand foreseen from the present to the 2030 scenario and subtracting it to the percentage increase in installed capacity. The result represents the necessary capacity to cover the Baseline demand given the decommissioning of most of the base generation capacity and the lower capacity factors of VRES in comparison to the thermal plants. Table 6, summarizes the assumptions regarding the generation mix and compares it with the Baselines scenarios.

Table 6. Generation capacity in Baseline and LVRES scenarios

	Baseline		**LVRES**	
Total Generation (MW)[a]	17,476		23,608	
Capacity by Type (MW)	**Installed Capacity**	**Percentage**	**Installed Capacity**	**Percentage**
Nuclear	5,919	34%	0	0.0%
Biomass	363	2%	833	3.5%
Waste and CHP	1,034	6%	1,815	7.7%
Geothermal	0	0%	95	0.4%
OCGT/CCGT	4,715	27%	5,490	23.3%
Other thermal	553	3%	61	0.3%
Run-of-River Hydro	86	0%	86	0.4%
Wind Offshore and Onshore	1,410	8%	8,770	37.1%
Solar	3,396	19%	6,459	27.4%

[a] Excludes PHES as this is considered as ESS in modelling.

The fuel costs, emission costs, and demand were maintained constant from the Baseline scenario in order to ensure comparability between the scenarios. Although a different generation mix is likely to impact the imports and exports, these were also kept constant to simplify the analysis. To include the effects of generation outages, the 2019 historical outage rate of each generation technology for each modelled day was calculated and assumed to remain constant in the LVRES scenarios.

The resulting supply and demand curves for the LVRES scenario are shown in Figure 9. It can be noted that all modelling days show a distinct peak in supply around midday, caused by the hours of high solar generation. There is also a general low supply during the early morning hours due to low wind and solar generation at said time. The Figure also shows that there are a few times when generation is not enough to cover all the demand. This can be seen in January around 9:00 am, June during the evening peak, and September during the hours of low solar generation.

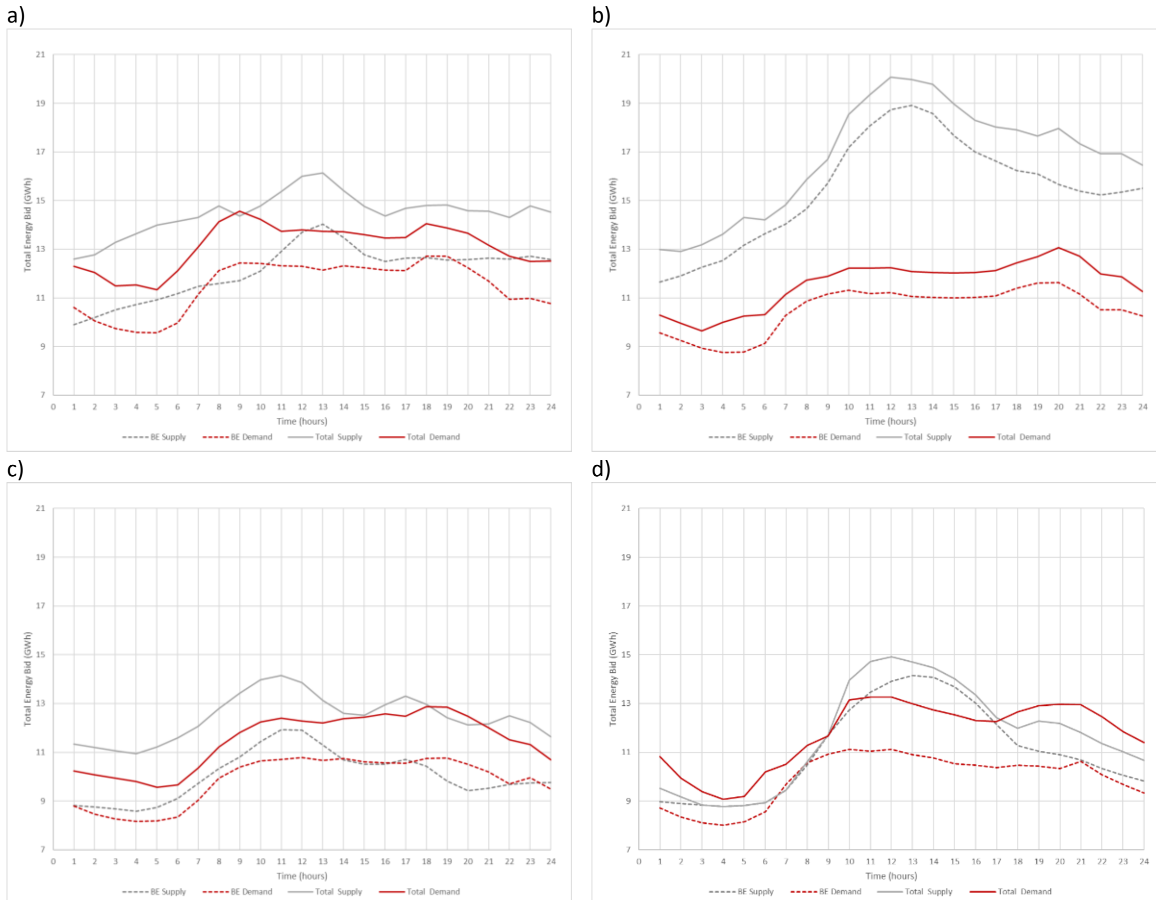


Figure 9. Belgium Supply and Demand and including imports and exports (Total Supply and Total demand) for the following modelling days: a) January, b) March, c) June and e) September.

The historical prices for the ESS operation optimization model of the LVRES scenarios could not be obtained from real data like in the Baseline case. Therefore, the resulting MCPs of the price-maker operation of the biggest existing PHES (Coo 1&2) with the LVRES generation mix was used as input for the model. Said MCPs can be comparable to the historical prices used for the Baseline scenarios because they both consider the generation mix of the scenario and the operation of the existing price-maker PHES capacity.

3.2.3 Storage Levels

Belgium currently has a 1.3 GW capacity of PHES divided in two storage plants, Coo 1&2 and Plate Taille. To assess the inclusion of large-scale ESS, the Baseline and LVRES scenarios described above were ran with no storage, the existing PHES, and three different ESS capacities, which were added considering three separately operated ESS. For the no-storage scenario, all storage, including the existing PHES capacity, was removed from the system. For the Low, Medium, and High storage scenarios, the existing PHES capacity was modelled next to 100, 500, and 1000 MW of new storage capacity in the form of Lithium-ion BESS with a four-hour duration, respectively. The duration represents a common upper limit for the chosen technology, and it was chosen based on literature's suggestion that the discharge duration should be between three and ten hours to better capture the benefits of energy arbitrage [1]. However, the effect of this was tested in the sensitivity analysis.

Given the 24-hour modelling timeframe, all ESS were assumed to have daily cycles, starting the day at their recommended DoD, which represents an empty storage. Table 7 includes the parameters of the ESS used in the model and Table 8 shows which of these plants were considered to be active in each storage level scenario.

Table 7. Parameters of ESS used for modelling.

Code	P_r	E_r	SOC_0	DoD	η_{ch}	η_{dis}	Ref.
Unit	MW	MWh	%	ratio	ratio	ratio	NA
Coo1 & 2	1164	5000	5%	0.95	0.87	0.87	[52], [53]
Plate Taille	144	796	5%	0.95	0.84	0.84	
BESS 1	100	400	10%	0.9	0.95	0.95	[1], [54]
BESS 2	400	1200	10%	0.9	0.95	0.95	
BESS 3	500	2000	10%	0.9	0.95	0.95	

Table 8. Active ESS and total capacity for each storage level scenario

Storage Level	Coo1 & 2	Plate Taille	ESS 1	ESS 2	ESS 3	Total Storage Capacity (MW)
No Storage	✗	✗	✗	✗	✗	0
Existing PHES	✓	✓	✗	✗	✗	1300
Low	✓	✓	✓	✗	✗	1300 + 100
Medium	✓	✓	✓	✓	✗	1300 + 500
High	✓	✓	✓	✓	✓	1300 +1000

3.3 Key Performance Indicators

The Key Performance Indicators (KPIs) shown in Table 9 were calculated for each scenario. The results were analysed and compared with existing literature to determine the effects of energy storage on consumers and producers in energy systems with different LVRES levels.

Table 9. Analysis KPI. Definitions based on Ref. [36]

KPI	Explanation
SEW	The overall benefit that arises from trading, equals the sum of consumer and producer surplus.
Consumer surplus (CS)	Benefit resulting from the difference between the amount that consumers are willing and able to pay for electricity (demand curve) and the market-clearing price.
Producer Surplus (PS)	Benefit resulting from the difference between the minimum price for which suppliers are willing to sell (assumed to be production costs) and the market-clearing price.
ESS Net Revenue (ESS R)	Net revenue resulting from the storage operation, considering charging and discharging costs.
Market-clearing prices (MCP)	Price in €/MWh at which demand equals supply.

For the purpose of this analysis, the SEW was calculated following the formulation used by Sioshansi [55] where the SEW is separated in consumer surplus, producer surplus, and ESS net revenue as shown in Equation 5a. The calculation of each of the mentioned elements composing the SEW is shown in Equations 5b to 5d. Separating the ESS net revenue from the consumer and producer surplus allows to better analyse the effect of storage in non-ESS market players.

$$SEW = PS + CS + ESS\ R \tag{5a}$$

$$PS = \sum_{t \in T} \left(\sum_{s \in S} \left(\lambda_t * Qs_{s,t} \right) - \left(Ps_{s,t} * Qs_{s,t} \right) \right) \tag{5b}$$

$$CS = \sum_{t \in T} \left(\sum_{d \in D} \left(Pd_{d,t} * Qd_{d,t} \right) - \left(\lambda_t * Qd_{d,t} \right) \right) \tag{5c}$$

$$ESS\ R = \sum_{t \in T} \left(\sum_{n \in N} \lambda_t \left(Qdis_{n,t} - Qch_{n,t} \right) \right) \tag{5d}$$

4 Results

Table 10 presents the KPIs obtained by modelling the scenarios using the price-maker approach. The difference in SEW, Consumer Surplus, Producer Surplus, and ESS Revenue (ΔSEW, ΔCS, ΔPS, respectively) were calculated in relation to the No Storage Level. It can be noted that the inclusion of ESS resulted in an increased SEW for most scenarios when compared to the No Storage case. Some exceptions are observed in the Medium and High storage levels of the LVRES scenario in March.

Table 10. KPIs for price-maker modelling. Differences (Δ) expressed in relation to No Storage level. All quantities are in thousands of € per day.

	Baseline				LVRES			
Storage Level	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**
				January				
No Storage	-	-	-	-	-	-	-	-
Existing PHES	102.75	766.21	-722.12	58.66	16.20	28.41	-27.86	15.64
Low	108.69	1,294.69	-1,247.24	61.23	20.56	131.10	-129.75	19.21
Medium	117.01	2,314.56	-2,216.90	19.35	32.13	353.14	-334.31	13.29
High	136.85	3,424.92	-3,298.32	10.25	38.30	388.51	-346.80	-3.41
				March				
No Storage	-	-	-	-	-	-	-	-
Existing PHES	0.00 [a]	0.00 [a]	0.00 [a]	0.00 [a]	1.54	279.81	-279.25	0.97
Low	2.92	249.25	-248.46	2.14	2.15	0.00	0.00	2.15
Medium	6.70	724.74	-714.02	-4.01	-0.58	0.00	0.00	-0.58
High	0.54	689.01	-677.54	-10.93	-6.20	0.00	0.00	-6.20
				June				
No Storage	-	-	-	-	-	-	-	-
Existing PHES	23.56	1,231.90	-1,211.06	2.72	45.64	-569.52	584.59	30.58
Low	26.60	1,061.90	-1,038.78	3.48	52.90	-561.86	576.86	37.90
Medium	25.83	1,112.90	-1,082.98	-4.08	63.13 [c]	645.13 [c]	-569.74 [c]	-12.26 [c]
High	26.22 [b]	1,304.32 [b]	-1,255.19 [b]	-22.91 [b]	90.47 [d]	-411.70 [d]	433.24 [d]	68.93 [d]
				September				
No Storage	-	-	-	-	-	-	-	-
Existing PHES	0.5 [e]	-2.8 [e]	2.9 [e]	0.4 [e]	1,774.18	99,194.45	-97,724.29	304.02
Low	2.4	132.7	-130.6	0.2	1,817.07	104,886.36	-103,428.73	359.43
Medium	10.3 [f]	190.8 [f]	-186.1 [f]	5.6 [f]	1,707.16	86,932.03	-84,914.27	-310.60
High	6.6	754.5	-725.5	-22.4	1,777.13	87,840.53	-85,835.89	-227.51

[a] Solver reached time limit and no values had been found for the optimal operation of Plate Taille, therefore it was assumed to remain non-operational.
[b] Solver reached time limit for optimal operation of Coo1&2; suboptimal values were used for this.
[c] Solver reached time limit for optimal operation of Plate Taille; suboptimal values were used for this.
[d] Solver reached time limit for optimal operation of BESS 4 and 5; suboptimal values were used for these. Solver reached time limit and no values had been found for Coo1 & 2, therefore it was assumed to remain non-operational.
[e] Solver reached time limit for optimal operation of Coo1&2; suboptimal values were used for this.
[f] Solver reached time limit for optimal operation of BESS 4; suboptimal values were used for this.

In most of the cases, adding large scale storage resulted transfer of surplus from the producers to the consumers, due to higher off-peak prices and lower on-peak prices. While there is a gain for producers in off-peak profits because of the storage charging operations, this is offset by the drop of the producer's on-peak profits, which tends to be larger because more energy is exchanged at these hours. However, this is not always the case as it can be seen in some of the analysed scenarios, such as the LVRES scenarios for June. Furthermore, it was found, in line with existing literature [9], [10], [12], that storage does not only redistribute wealth by transferring part of the producer's surplus to the consumers, but it also creates welfare by displacing high-cost generation with low-cost technologies, avoiding high MCPs.

The results also showed that the magnitude of the SEW effects and ESS net revenue are highly sensible to the other market bids. This is mainly due to the effect of the generation mix and available capacities on the resulting MCPs. The previous caused important differences in the SEW effects of large-scale storage for the same modelling dates in the Baseline and LVRES scenarios.

For example, the Belgium market clearing model showed that Baseline MCPs without storage tend to fluctuate mainly in relation to the demand bids, with some peaks around 9:00 am, and 18:00 pm. In comparison, in the without storage case of the LVRES scenarios, MCPs are highly influenced by solar and wind availability. In their study of the Spanish market, Cerezo Et Al. [10] found that this dependency of prices on stochastic resources increases price volatility, benefiting the storage arbitrage profits. However, in this case study of the Belgian DA market, the previous did not hold for the modelling dates with high wind availability (i.e., January and March) due to the relatively constant resource availability throughout the day. Still, the ESS net revenues and SEW benefits for the LVRES scenarios were significantly higher than in the Baseline scenarios for the modelled days with high solar generation and low wind availability, such as June and September. The previous showed that the addition of storage is especially valuable for summer days, where there is low wind and high solar availability.

Regarding the storage levels, the results showed that the SEW tends to increase with the addition of storage capacity since it generally led to less volatile market prices. As the number of players increases, the impact that each player has on the price reduces, and therefore their market power, benefiting the overall SEW [9]. Nevertheless, this also results in lower potential arbitrage values from the use of storage and decreased storage net revenues per installed MW, leading in some cases to losses for the storage owners.

In the cases where the differences in on-peak and off-peak prices were small, such as the March Baseline scenario, it was found that BESS were able to better capture the potential arbitrage value due to their higher efficiency. On the other hand, the PHES used little capacity or remained non-operational. The previous resulted in higher gain of SEW in the scenarios including the BESS technologies than in the Existing PHES scenarios.

The modelling results for each modelling day are described in detail below. For these, the MCPs of the no storage scenarios are described in the context of each modelling day market conditions. Then the storage effect in the MCPs prices is analysed and related to the ESS' operation and the resulting changes in consumer surplus, producer surplus, and SEW.

4.1 January

The MCPs for the Belgian DA Market for the January modelling day for both, the Baseline and the LVRES scenarios, are shown below in Figure 10. The prices with No Storage in the Baseline scenario dropped in the early morning hours and showed a peak around 9:00 am, corresponding to the increased demand in the morning peak, and from 13:00 to 23:00, due to a lower availability of generation at said time and increased demand during the evening. The addition of storage to the system resulted in a higher minimum price and a lower maximum price. This levelling effect in the prices was greater in the scenarios with more storage capacity. This change in prices, however, negatively affects the ESS net revenues by reducing the potential value of arbitrage. This caused a decreased use of storage capacity (see Figure 11) and less ESS net revenues as the installed capacity increases.

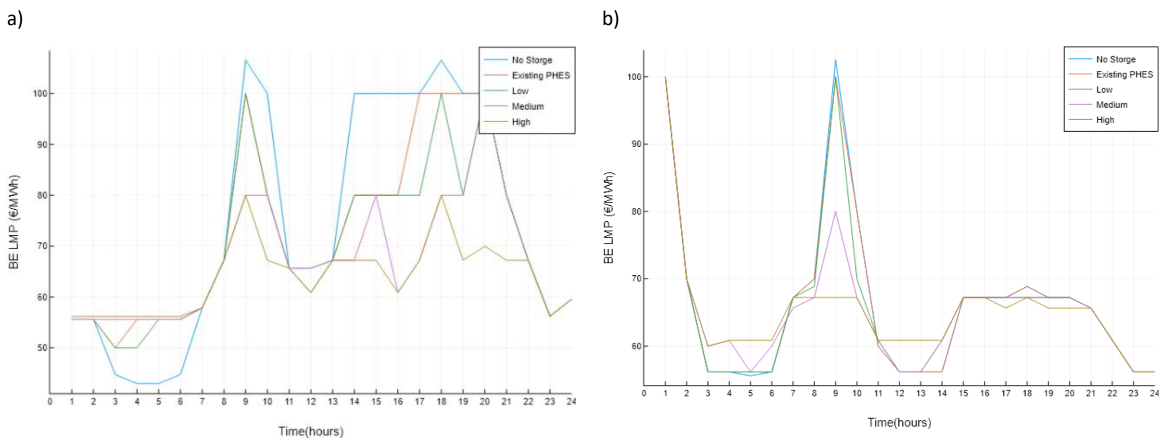


Figure 10. MCPs of January modelling day for a) Baseline Scenarios and b) LVRES Scenarios

As it can be noted in Table 10, there was also an increase in the SEW of the Baseline scenarios due to the added storage capacity. Around 50% of this increase is composed of the ESS net revenue for the Existing PHES and Low storage levels, and the rest is a result of net gains in consumer surplus. There were lower ESS net revenues for the Medium and High storage levels, and these represent under 10% of the increase in SEW, while the rest is net gains in consumer surplus. In all these cases, the consumer surplus gains, and the producer surplus losses as the result of decreased prices during on-peak periods or periods with low generation. While there were also increased off-peak prices, the consumer losses related to these are lower than the gains because of the aforementioned on-peak effect.

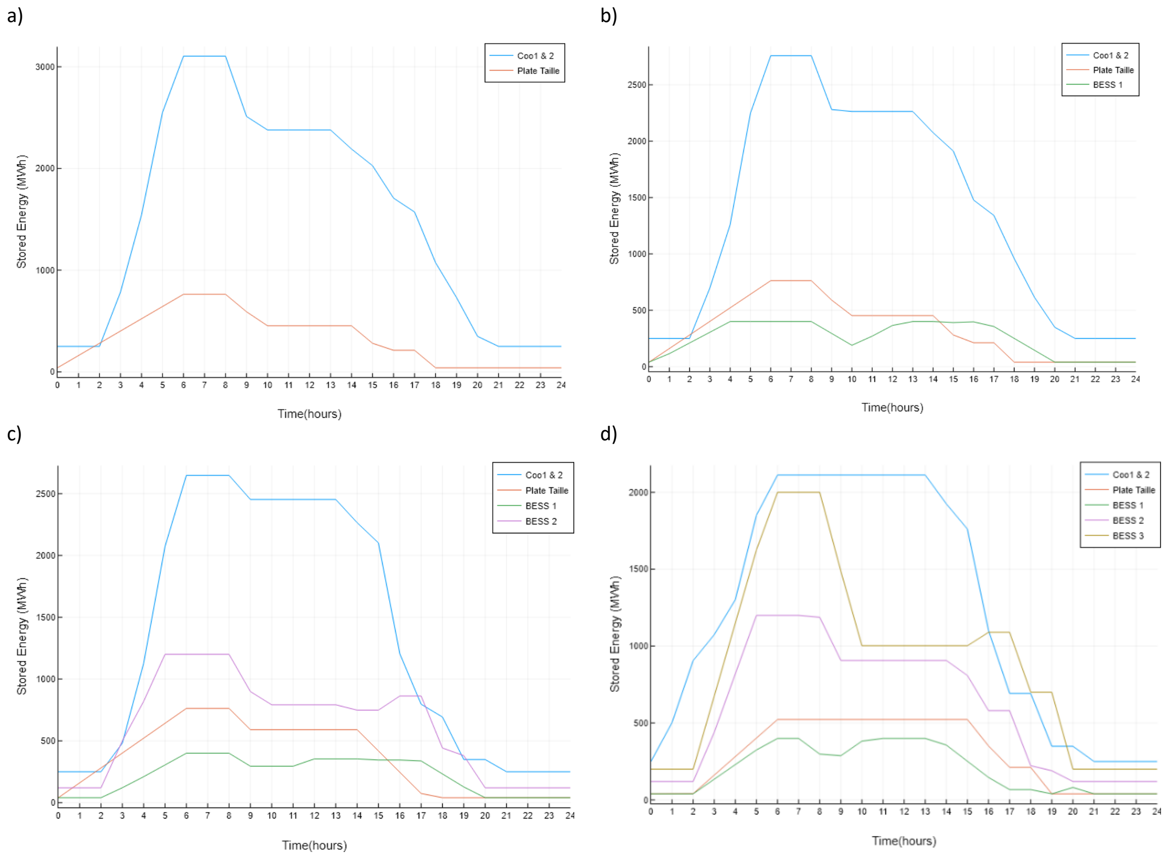


Figure 11. ESS operation for January modelling day in the Baseline scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

The MCPs for the LVRES No Storage scenario had a similar pattern that in the Baseline scenario but a different scale, affecting the distribution of consumer and producer surplus and the potential arbitrage value. There was a high peak in the prices for the early hours of the day that is not present in the Baseline scenarios. This was caused by the low LVRES generation availability at that time. While there is still a price peak at 9:00 am, there is no significant price increase in the evening hours because of the high wind generation. A price levelling effect with the addition of ESS can also be noted in these scenarios, being clearer for the High storage level scenario.

Similarly to the Baseline, there is a net increase in SEW with the inclusion of storage. This increase is even larger for the scenarios with higher storage capacity. However, the SEW benefits gained in the LVRES are considerably lower because of the reduced arbitrage potential caused by the stable prices at the evening peak. Figure 12 illustrates the ESS' stored energy throughout the January modelling day for the LVRES scenarios. It can be noted that the LVRES scenarios also results in less operation hours for the PHES storage in the Existing PHES, Low, and Medium scenarios, and no operation at all in the High scenario. The BESS, on the other hand, operated with two charging and discharging cycles.

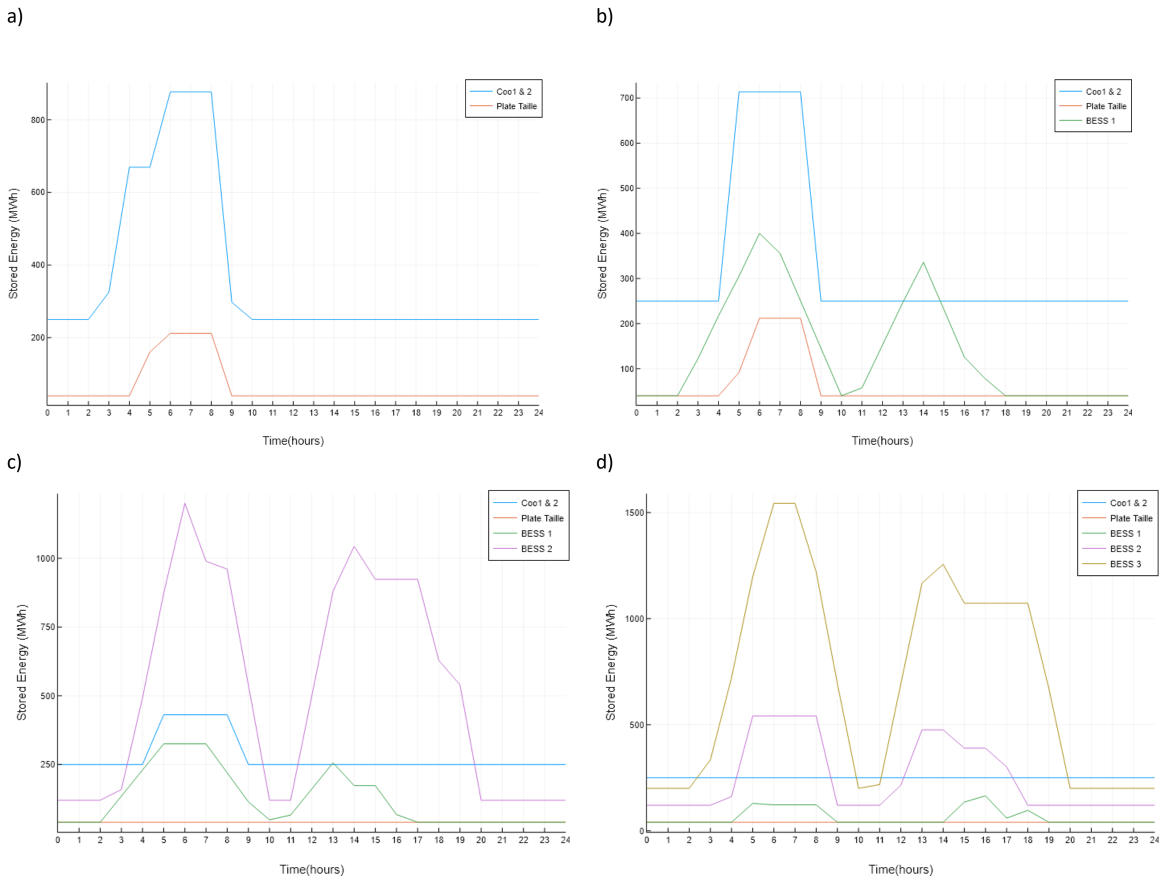


Figure 12. ESS operation for the January modelling day in the LVRES scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

4.2 March

The resulting No Storage MCPs for the Belgian DA for the March modelling day were very different for the Baseline and the LVRES scenarios, as shown in Figure 13. The MCPs of the Baseline No Storage scenario remained between 40 and 55 €/MWh, with high prices at 7:00 and 9:00, and again at the evening demand peak between 17:00 and 22:00. There were also price drops at the early hours of the day when there is low demand, and around midday, when there is high VRES availability. The slight difference between the off-peak and on-peak prices resulted in a low potential arbitrage value that limited the revenue opportunities for the ESS and the SEW benefits from their operation.

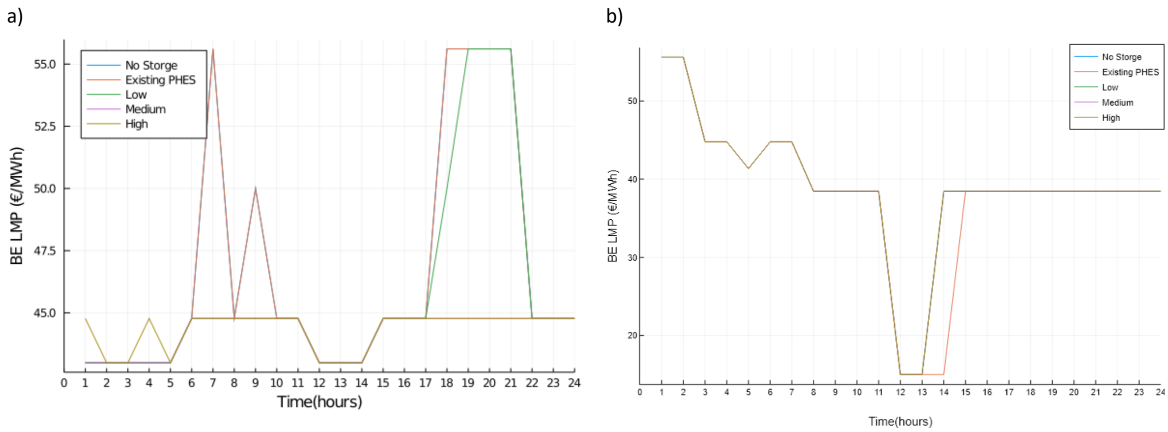
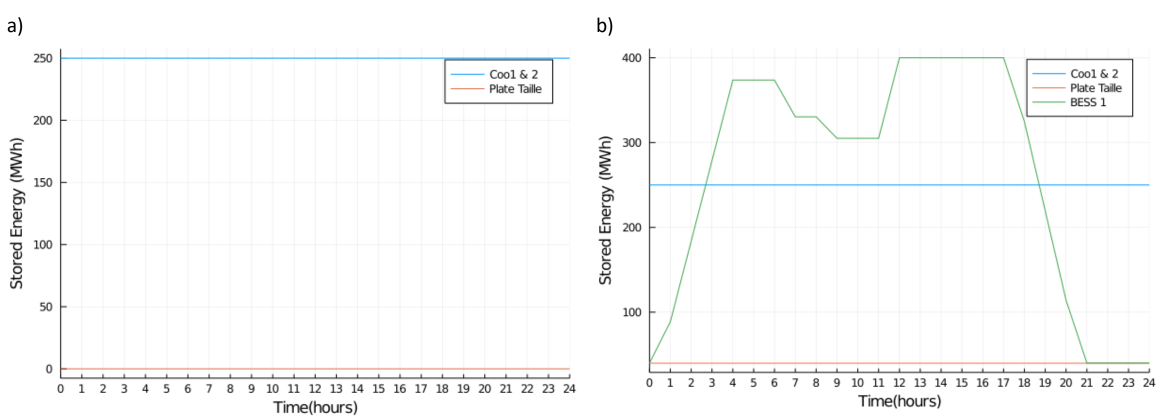


Figure 13. MCPs of March modelling date for a) Baseline Scenarios and b) LVRES Scenarios

For the Existing PHES storage level scenario, Coo 1 & 2 and Plate Taille remained non-operational as shown in Figure 14. This status can be explained by their low round trip efficiency, which does not profit from the slight price difference. Since there was no operation, there was no change in the MCPs and the SEW for this storage level.

Adding a small BESS did result in a net gain in SEW, even though this is minimal. The addition of the 100 MW BESS for the Low storage level scenario reduced the morning prices occurring at 7:00 and 9:00, as well as the evening high price at 18:00. However, its discharging was not enough to cause a difference in the high prices between 19:00 and 21:00, resulting in a profit for the BESS.

The Medium storage level resulted in a more considerable SEW increase due to the consumer gains of lowering the high prices with the morning and evening peak. However, the charging and discharging price difference did not offset the losses caused by the charging and discharging efficiency, resulting in a negative ESS revenue. The same happens for the High storage level scenario.



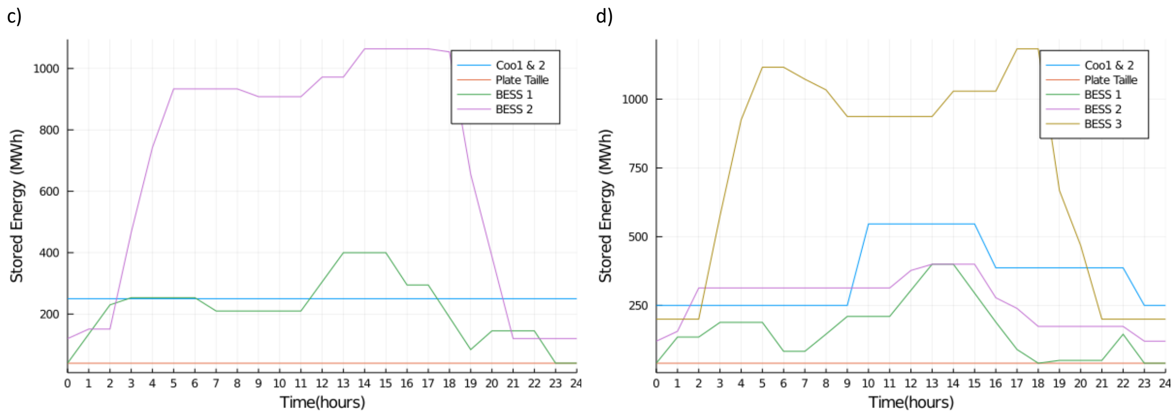


Figure 14. ESS Operation for March modelling day in the Baseline scenario with the following storage levels: a) a) Existing PHES, b) Low, c) Medium, and d) High

The No Storage MCPs for the LVRES scenario presented a different pattern than the Baseline case because the larger VRES share in the mix caused a more significant influence of solar and wind availability in the prices. The early morning hours presented a high price due to the lower wind production and the null solar generation at said time. There was an important price drop of 23.4 €/MWh at midday because of the high wind generation combined with the hours of larger solar generation. As shown in Figure 15, the ESS used this price drop to charge at low energy cost and store the excess VRES generation, and discharge between 15:00 and 17:00 as the generation decreases.

For the existing PHES storage level scenario, there was a minor operation of PHES between 11:00 and 14:00, leading to the price dropping at 14:00, resulting in consumer surplus gains and producer surplus losses. For the rest of the storage levels, there is no change in the MCP with the ESS operation, resulting in no changes in consumers and producer's surplus but in losses for the ESS, which expected a larger price difference in their operating hours because they are considering that the other BESS operate with a price-taker approach. The operation of price-maker storage with the Level 1 assumption does not have benefits for this modelling day in the LVRES scenarios.

There was also some arbitrage potential with the higher energy prices at the early hours of the day that could have been a revenue opportunity or the ESS and have positive SEW effects. However, the ESS modelled could not take advantage of the morning high prices, since it was assumed that they start the day empty.

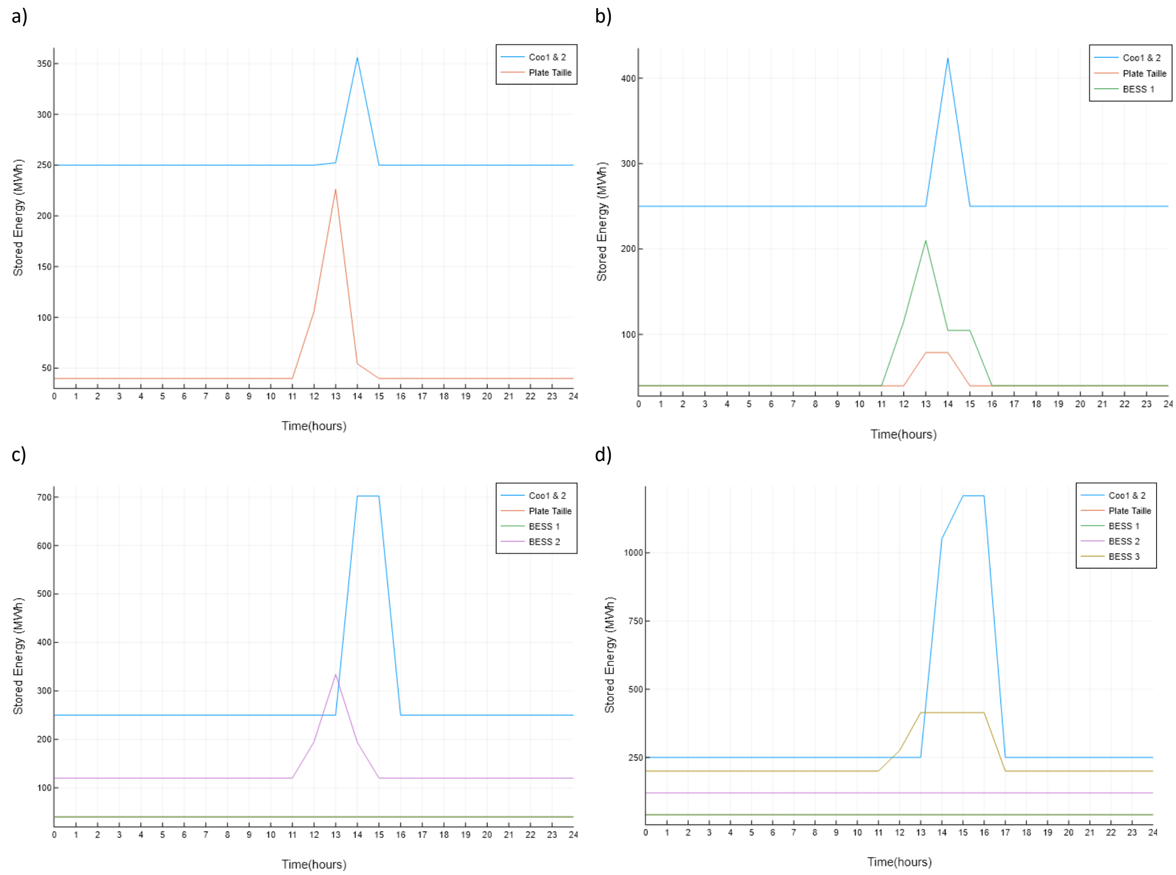


Figure 15. ESS Operation for the March modelling day in the LVRES scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

4.3 June

The June modelling day MCP for the Baseline and the LVRES both followed a pattern of generally low prices before 12:00 and some hours of peak prices between 13:00 and 22:00. However, the prices in the LVRES oscillated between higher values and showed a smaller difference between the on-peak and off-peak prices. The previous can be seen in Figure 16 below. Despite the apparent smaller potential arbitrage value in the LVRES scenarios, the addition of storage resulted in a greater gain of SEW for all the storage levels than in the Baseline scenarios.

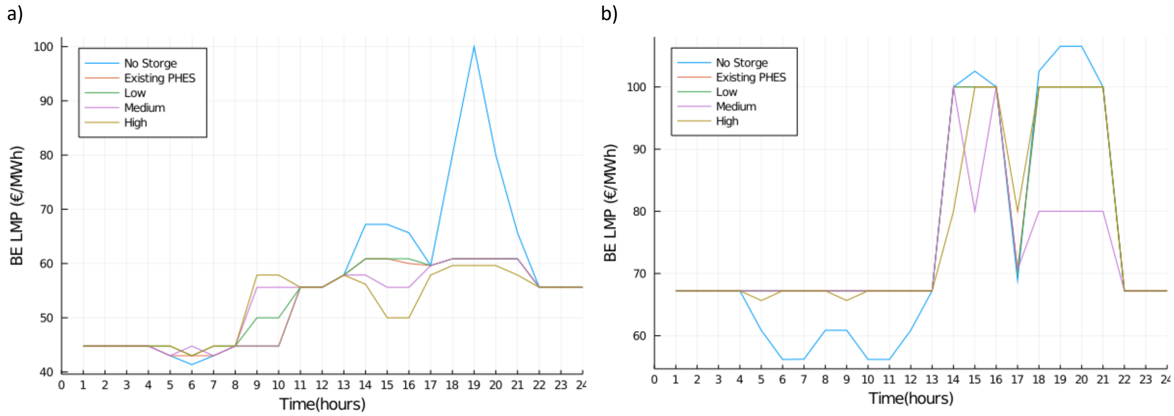
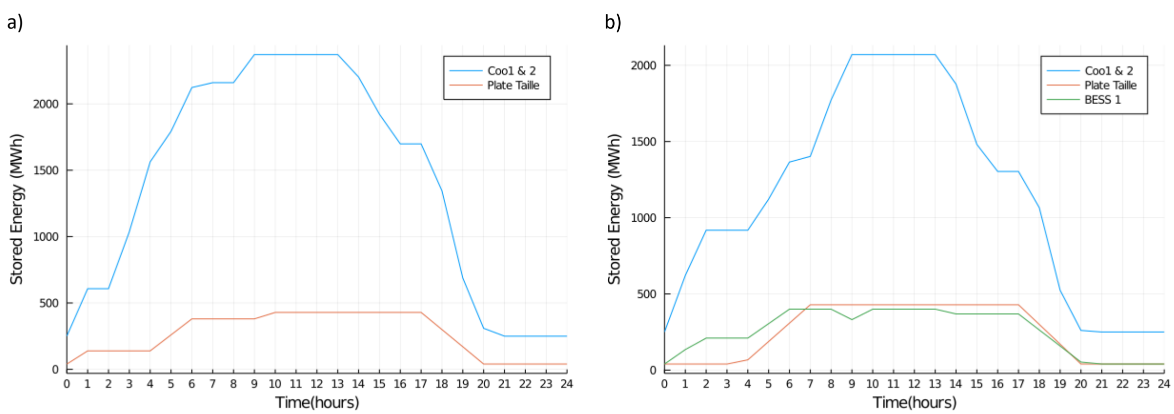


Figure 16. MCPs of June modelling date for a) Baseline Scenarios and b) LVRES Scenarios

The gains in SEW in the Baseline case were almost identical for the Low, Medium, and High storage levels scenarios, the lowest being the Existing PHES scenario. Despite the similar changes in SEW for all Baseline scenarios, there are differences in the producers and consumers gains and the ESS net revenues. The Low storage level resulted in the highest ESS net revenues per MW of installed storage as well as the most SEW gains per MW of installed storage (2.48 and 18.91 €/MW respectively). The operation of the Existing PHES and Low storage level helped level the prices by increasing the MCP in the off-peak hours and reducing them in the on-peak hours. The ESS in these scenarios mainly charged during the first half of the day, when there was an excess supply and low MCP, and discharged during the second half, when there is a supply shortage, as shown in Figure 17.

For the Medium and High storage scenarios, the ESS operation further increased the off-peak prices and reduced the on-peak prices to the point that the former was higher than the latter. This resulted in negative ESS net revenues. However, the decreased on-peak prices highly benefited consumers.



c) d)

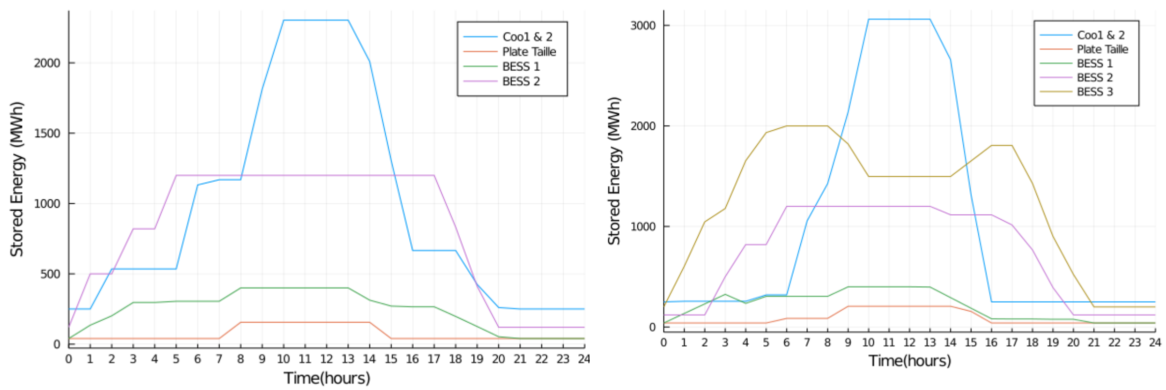
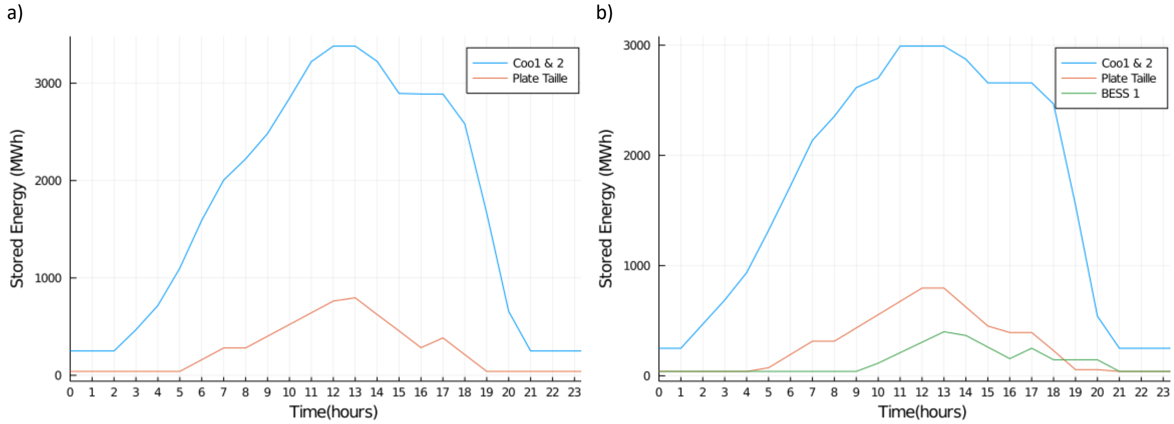


Figure 17. ESS Operation for June modelling day in the Baseline scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

The SEW benefit of adding electricity storage in the LVRES scenarios increased as more storage capacity was added, with the highest gained benefit being from the High storage level, most of which is caused by the ESS high revenues. In this storage level, Coo1 & 2 remained non-operational as it can be seen in Figure 18. It is important to note that this could still not be the optimal operation for said ESS since the operation optimization did not reach feasible values during the set optimization time. However, this storage level still resulted in the highest profits per installed MW of storage but not the greatest benefit for the other market participants. The greatest benefit for other market participants can be found in the Medium storage scenario, where there are consumer surplus gains because of lower on-peak prices, but negative ESS revenues.

It is worth noting that, differently from most of the other scenarios, the Existing PHES, Medium, and High storage levels result in a loss of consumers surplus and a gain of producer surplus, while the ESS is also making a profit. This combination can only be seen in this case and results from the ESS increasing the off-peak prices while maintaining high on-peak prices. This is only possible because of the considerable lack of supply during the evening hours and enough supply during the charging hours, at times of high solar generation.

a) b)



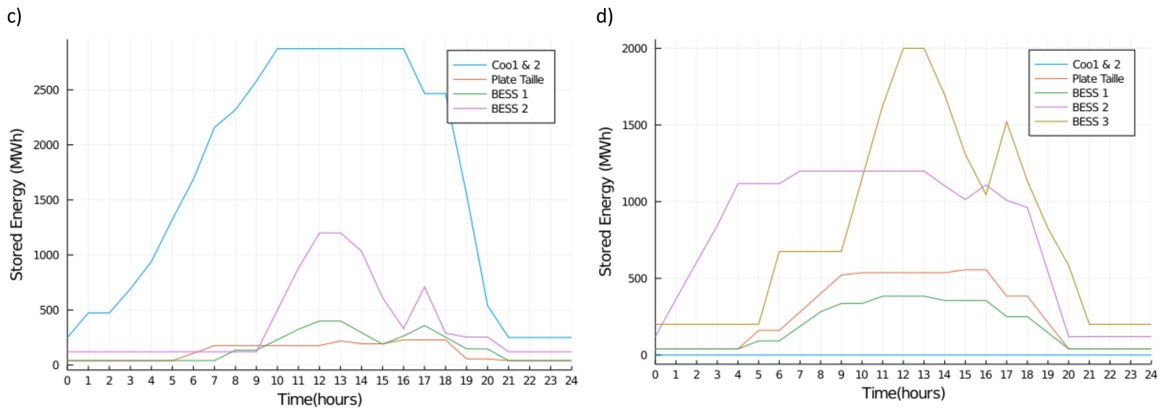


Figure 18. ESS operation for the June modelling day in the LVRES scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

4.4 September

The No Storage MCPs resulting from the Baseline and LVRES modelling show the most significant difference, compared to the other modelling dates, as shown in Figure 19. For the Baseline case scenario, the difference between the highest and the lowest price during the day is only around 15 €/MWh. In comparison, the MCP for the LVRES reached the market price cap of 3000 €/MWh for 5 hours during the modelled day, which means that there was a very high potential value in energy arbitrage for this day.

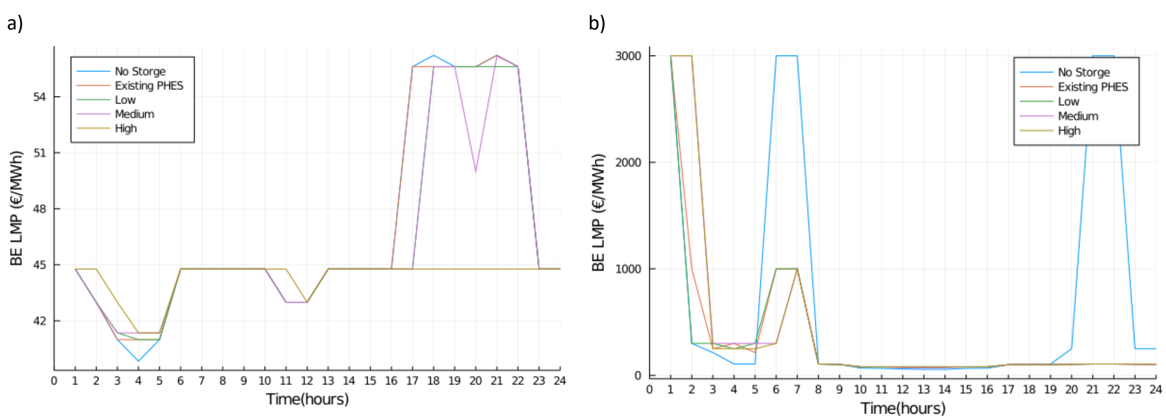


Figure 19. MCPs of September modelling date for a) Baseline Scenarios and b) LVRES Scenarios

Figure 20 illustrates the resulting ESS operation for the Baseline scenarios. As it can be noted, the slight price difference between on-peak and off-peak hours led to Plate Taillie remaining non-operational in every storage level scenario, most probably due to its low efficiency that did not allow to profit from arbitrage opportunities. Similarly, there is little operation from Coo 1 & 2, only reaching an energy state of 700 MWh, little over 14% of SOC. On the other hand, the BESS have a higher roundtrip efficiency and operated up to 100% of their SOC in the Low, Medium and High storage level scenarios. However, the BESS operation resulted in little change in the MCP in comparison to the No Storage scenario. Therefore, there is little change in the SEW because of the inclusion of storage for this modelling day.

The High storage level scenario is the one that most benefited the consumer by lowering the MCPs for the evening peak hour. However, this already led to losses for the ESS as a result of their operation.

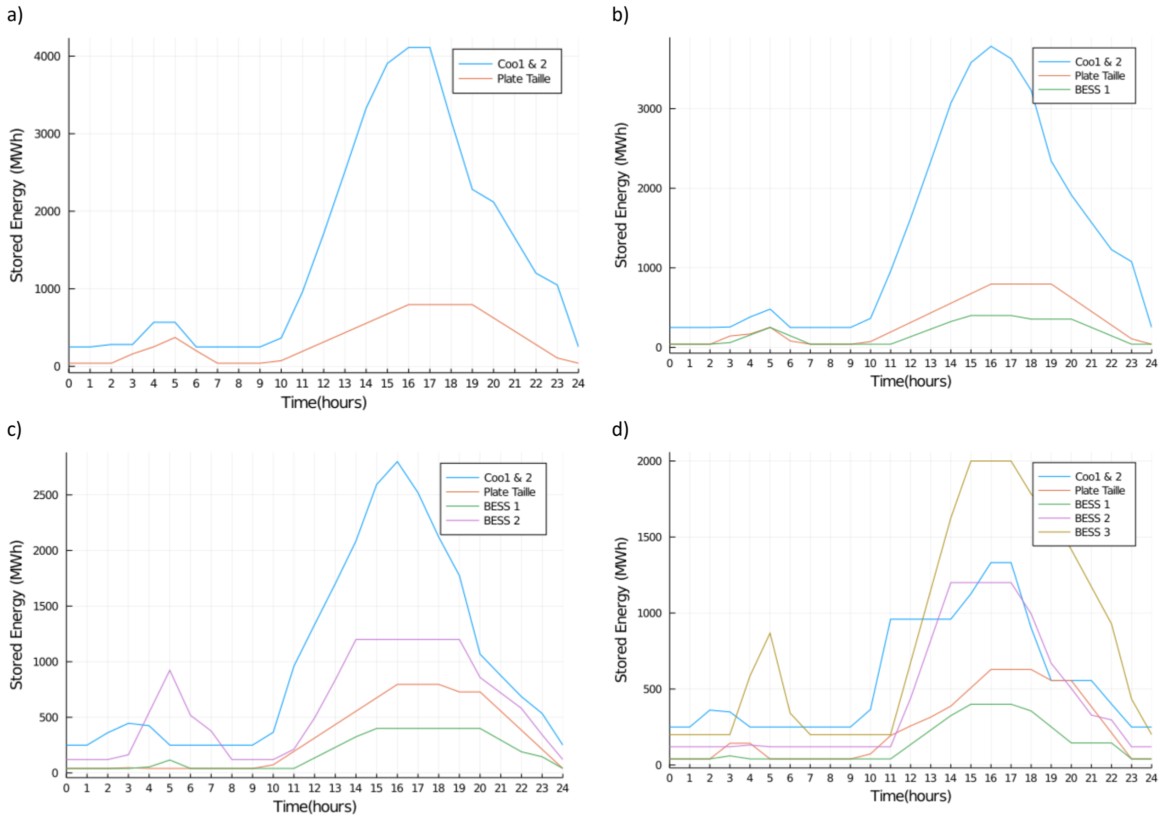


Figure 20. ESS operation for the September modelling day in the LVRES scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

The greatest increase of SEW when adding storage was seen in the LVRES scenarios for the September modelling day. The low wind and high solar availability resulted in a generation shortage during the dark hours of the day and an excess of production around midday. The results were MCPs that, without storage, would reach the price cap of 3000 €/MWh at the morning and evening demand peaks. However, the inclusion of storage reduced the price increase during the morning peak and almost eliminated the price increase during the evening peak, representing a significant gain for consumers and a significant loss for producers in comparison to the no storage scenario. The difference between the charging and discharging prices allowed the ESS to profit from the energy arbitrage in the Existing PHES and Low scenarios, but not in the Medium and High storage level scenarios. In the latter, the storage operation, shown in Figure 21, reduced the evening on-peak price from 3000 €/MWh to 107 €/MWh, a price similar or even lower than the price at the morning hours, when they charged, leading to a negative ESS net revenue.

It can also be noted that, even with the storage operation, the price cap is still reached during the early morning hours. This is because of the assumption that the ESS start the day empty. However, in cases of high solar, the ESS would most probably change its charging pattern to profit from the high prices in the early morning if multiple days were modelled. The effects of changing this assumption for days with high solar was tested in the sensitivity analysis.

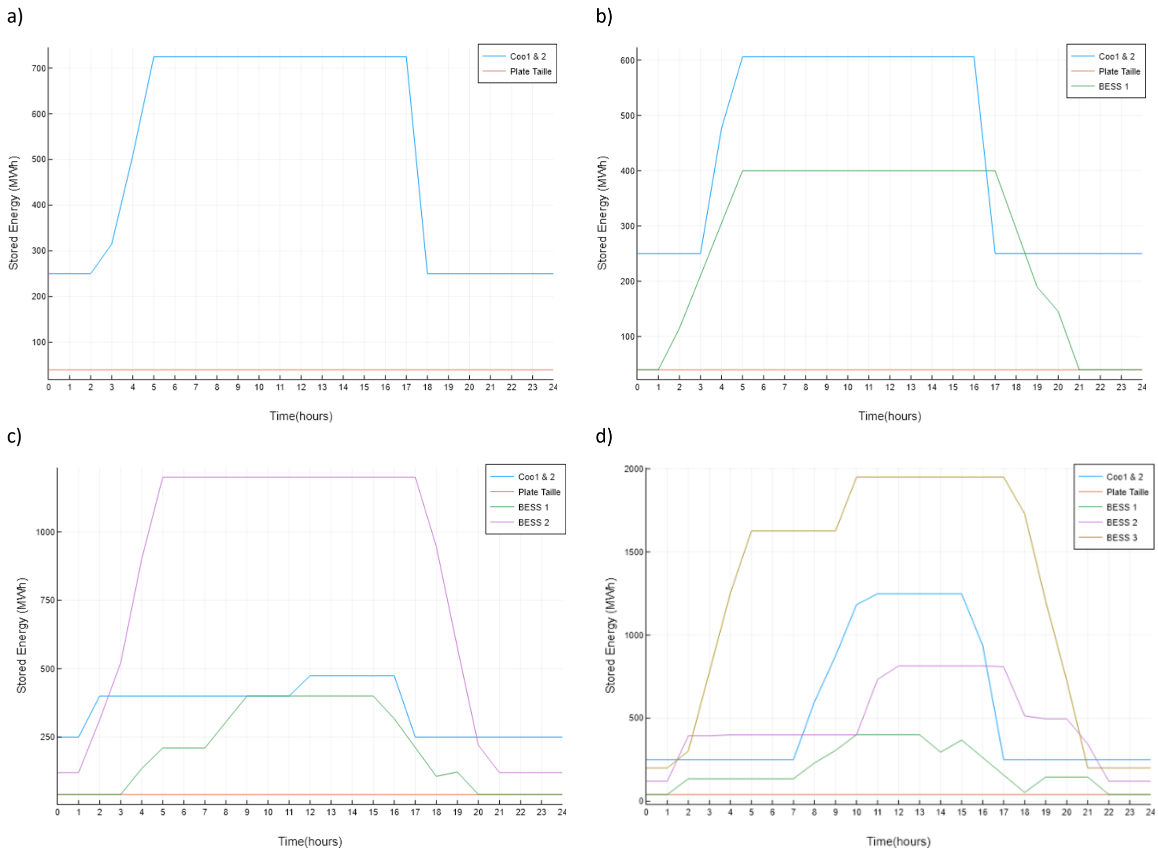


Figure 21 Price-maker ESS Operation for September modelling day in the Baseline scenario with the following storage levels: a) Existing PHES, b) Low, c) Medium, and d) High

4.5 Effect of Price-taker vs. Price-maker storage operation

Formulating, programming, testing, and running the Belgian market clearing model with the price-taker strategy of ESS was a first step towards creating the price-maker model used to answer the research question. Appendix C shows the KPI values for all the modelling scenarios using the price-taker approach.

With this approach, adding large-scale ESS to the Belgian electricity system only increased the SEW for the Existing PHES, Low, and Medium storage levels modelled in January for the Baseline scenarios. The SEW for the rest of the modelled dates decreased by the addition of storage.

While this seems to differ from the conclusions reached in previous research such as, Shoshoni's statement: "*if the generation sector is perfectly competitive and does not own storage, then storage cannot be welfare-diminishing*"[55], the decreased in SEW can be explained by examining the different elements that constitute the calculation of the SEW and the price-taker approach assumptions.

In all scenarios, the storage operation generally benefited the non-ESS market players. The addition of consumer surplus and producer surplus (ΔCS+ΔPS) in all the scenarios resulted in a positive number, representing an overall benefit for the market. However, when the ESS revenues were added, the SEW was negatively affected because the storage losses were greater than the gains of other market players.

Even in the cases with a net gain in the SEW, a privately owned large-owned ESS could not be economically viable if the storage operates as a price-taker due to the negative revenues. These losses resulted from operating an ESS (large enough to affect the market clearing prices) with a price-taker approach. In this regard, the charging operations increased the demand enough to drive the marginal prices up, and the discharging operations increased the supply enough to cause a drop of the marginal prices. This effect increased with the addition of more storage using a price-taker approach. Consequently, ESS effectively charged when there were high prices and discharged with low prices, the opposite of what is necessary to maximize the profit. Because of the previous the price-maker operation is a more realistic representation of the operation and scheduling of privately owned large-scale storage.

While the added SEW of the price-taker model resulted lower than for the price-maker scenarios, the benefit for the other consumers or producers was greater for the former case. This is because a price-maker storage avoids decreasing the off-peak prices and decreasing the on-peak prices as much as possible in order to maintain a high arbitrage value and, therefore, obtain higher net revenues. This, however, limits the welfare benefits for other markets players and could even lead to increased costs and consumer payments [8], [9], [24].

Since price-maker storage systems control its operation to obtain the maximum arbitrage value, results showed that price-maker storage made less use of its storage capacity and operated for shorter hours or less cycles than a price-taker storage in an attempt to limit their effect in the high or low prices. According to existing research [56], this can lead to the integration of less wind and solar power, leading to more energy curtailment, in comparison to the price-taker approach. This, however, was not the case for the Belgian market for the modelled days because the VRES generation was lower than the demand at all times for all scenarios, being completely dispatched even in the cases of no storage.

5 Sensitivity Analysis

A sensitivity analysis around the key ESS modelling assumptions was conducted to assess some of the model's uncertainties. As mentioned in Section 4, one assumption that can have an important effect on the results, especially in the days with high solar generation, is the initial SOC of the ESS. To test the effect of the initial SOC, the model was run again for the September modelling day assuming that all the ESS units start and finish the day with 30% of their storage capacity instead of empty, the resulting KPIs are shown in Table 11. This reflects the cycle that storage systems will most likely follow during periods of high solar generation and low wind generation, charging during the day and discharging during the night and early morning hours.

When comparing the results shown in Table 11 with those in Table 10, it can be noticed that the SEW increments due to storage generally increased with the assumption that the storage starts the day with a 30% SOC. Even though the increase is minimal for the Baseline scenarios, this is significant in the case of the LVRES scenarios. The energy stored by the ESS at the beginning of the day was discharged between 1:00 and 2:00, reducing the high morning prices, then the storage charged again in the high solar generation hours and discharged up to a SOC of 30% during the evening. The result of said operation was a levelling of the prices that eliminated all the 3000 €/MWh price peaks, as it can be seen in Figure 22, and greatly benefited the consumers. It is worth noting however, that the net revenues of the LVRES Existing PHES and Low scenarios were lower in the case of the 30%

initial SOC. Therefore, this might not be their preferred operation even though it is socially more beneficial. In order to test this, the ESS scheduling optimization would have to be run for multiple days.

Table 11. KPIs for price-maker modelling with an initial and final SOC of 30% for September. Differences (Δ) expressed in relation to No Storage level. All quantities are in thousands of € per day.

	Baseline SOC_0 = 30%				LVRES SOC_0 = 30%			
Storage Level	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**
No Storage	-	-	-	-	-	-	-	-
Existing PHES	0.00	0.00	0.00	0.00	3,077.66	145,933.60	-143,092.09	236.15
Low	3.65	138.40	-135.73	0.98	3,102.39	148,069.90	-145,171.99	204.48
Medium	12.48	120.34	-115.86	8.00	3,094.93	148,649.44	-145,849.32	294.80
High	17.43	123.49	-117.96	11.89	3,068.09	140,747.40	-138,190.90	511.59

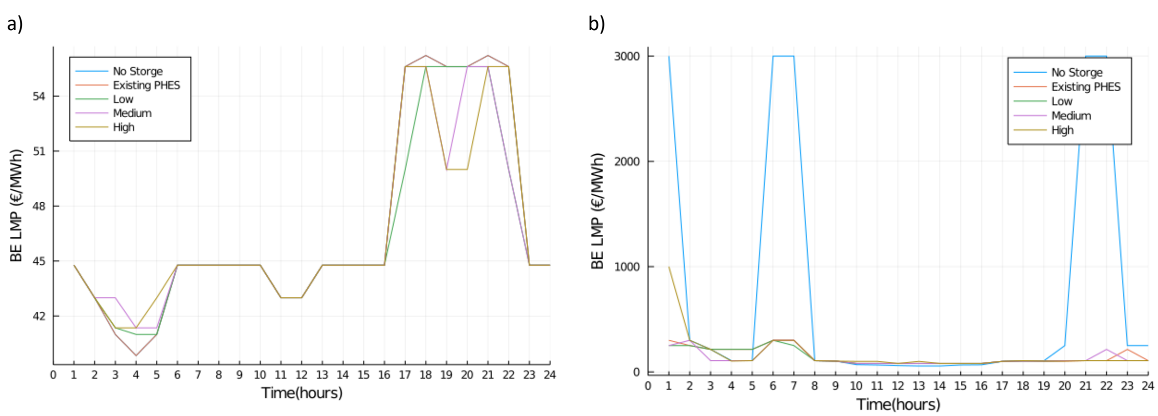


Figure 22. MCPs of September modelling date assuming and initial and final SOC of 30% for a) Baseline Scenarios and b) LVRES Scenarios

Another assumption made for the analysis is that the BESS's charging/discharging duration was of 4 hours, which is within the preferred range for energy arbitrage [3], [57]. However, BESS can be used for multiple market applications, one of which is as supplier of reserve services in the balancing market. A study of the role of electricity storage in the Belgian market considering short-term operation and long-term planning [58] found that PHES and BESS complement each other providing flexibility services, using PHES with long discharge durations for energy arbitrage and BESS with short discharge durations for frequency control. Said study found that for a high VRES penetration level the optimal BESS duration would range between 1.10 and 2.26 hours. While the BESS would mainly be used for provision of reserve services, the BESS could also participate in energy arbitrage, stacking revenues. Based on the previous, the January modelling date was run for BESS of 2-hour duration instead of 4-hours to shed a light on the difference between the effects of short term vs. mid-term storage in the DA markets. For this, the rated power of the BESS was kept constant, and the energy capacity was adjusted to obtain the desired duration. Table 12 shows the resulting KPIs for the January modelling day.

Table 12. KPIs for price-maker modelling with BESS of 2-hour duration for January. Differences (Δ) expressed in relation to No Storage level. All quantities are in thousands of € per day.

	Baseline				LVRES			
Storage Level	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**
No Storage	-	-	-	-	-	-	-	-
Existing PHES	102.75	828.86	-791.86	65.75	16.20	28.41	-27.86	15.64
Low	106.25	1,005.07	-963.44	64.61	19.14	181.83	-180.83	18.14
Medium	109.95	1,786.09	-1,702.75	26.62	29.52	550.42	-535.71	14.82
High	112.19	3,198.56	-3,067.71	-18.66	37.77	395.85	-361.27	3.19

As it can be seen by comparing Table 12 with the results shown in Table 10, for the case of January, SEW benefits reduced when using a BESS duration of 2-hour instead of 4-hour. However, the reduction is small for most of the scenarios, the highest being of 20%.

Finally, the effect of the BESS efficiency was tested. Even though, Li-ion batteries have a high roundtrip efficiency in comparison to other storage technologies, large systems are normally coupled to the grid through power conversion systems and Balance of Plant (BOP) systems (normally including elements such as transformers, switchgear, and cables), and need temperature control (heating and cooling). These elements also have an energy loss, dependent on design choices, that affects the storage round trip efficiency [59]. Given that Li-ion BESS can have a different range of efficiencies, the modelling day of March was run with a more conservative round trip efficiency of 83%, compared to the 90% used for the modelling of the results. Table 13 shows the resulting KPIs.

Table 13. KPIs for price-maker modelling with BESS with a round-trip efficiency of 83%. Differences (Δ) expressed in relation to No Storage level. All quantities are in thousands of € per day.

	Baseline				LVRES			
Storage Level	ΔSEW	ΔCS	ΔPS	ΔESS R	ΔSEW	ΔCS	ΔPS	ΔESS R
No Storage	-	-	-	-	-	-	-	-
Existing PHES	0.00	0.00	0.00	0.00	1.54	279.81	-279.25	0.97
Low	1.24	130.34	-129.90	0.79	1.45	0.00	0.00	1.45
Medium	2.56	342.97	-337.99	-2.41	-0.84	0.00	0.00	-0.84
High	-4.17	260.92	-255.49	-9.59	-5.42	0.00	0.00	-5.42

Comparing the obtained modelling results shown in Table 10 with the ones presented in Table 13, it can be noted that the decreased BESS roundtrip efficiency resulted in a lower SEW benefits, as well as and a reduced wealth transfer from producers to consumers, for all the March modelling scenarios except for the LVRES High storage level scenario. The reduced BESS efficiency prevented it from benefit from small arbitrage values, leading to fewer cycling and use of storage capacity. This analysis showed that the technical characteristics of ESS can have a significant effect on the storage operation when there is a small potential arbitrage value.

6 Discussion

The results of the present work suggest that there is an added societal value on the energy arbitrage participation of large-scale ESS in the electricity markets for both the current system and a system with a large participation of VRES. For the latter, large-scale ESS participation will have an essential role in levelling the prices caused by the daily cycling in solar energy availability. As such, it is recommended that policymakers and market regulators work to facilitate the participation of these technologies in the electricity markets. In this regard, the research also showed that the price-maker ESS player's profit maximizing objective does not always align with the optimal solution from the SEW perspective. Therefore, it is important to explore market structures or initiatives that incentivize the optimal social operation of large-scale ESS. For example, Contereras Et Al. [60] propose a non-uniform pricing scheme for ESS that can be designed to mitigate the adverse welfare impacts of the strategic operation.

Further, the results showed that the price-maker approach leads to the ESS player not using the full storage capacity to avoid reducing arbitrage value, limiting the amount of shifted energy and the SEW benefits. Consequently, it is also recommended that policymakers consider developing mechanisms to distribute the capacity of large-scale systems between different storage merchants to achieve greater SEW benefits and avoid the concentration of market power. The last can be done, for example, with the use of storage capacity tendering. However, that solution might be unviable from an investment perspective, which was not studied in the present research, especially considering the reduced net revenues per MW of installed storage with the addition of extra capacity.

For the specific case of Belgium, there were plans to expand the Coo1&2 PHES to add storage capacity to the electricity system [53]. However, based on the current work findings, the last would not be recommended as the model did not fully use the existing Coo 1&2 PHES capacity, even for the LVRES scenarios. Furthermore, that would result in a larger concentration of storage units and market power. Existing literature agrees that the addition of market power tends to result in deviations from the socially optimal system operation [9], [10]. The recommendation from the SEW perspective would be to invest, instead, in the research and development of smaller large-scale ESS such as BESS.

Furthermore, these results only measure the societal value of one of the multiple large-scale storage applications. Therefore, the societal value would be expected to increase when considering balancing, ancillary, and grid services. Given the potential social benefits of this technology, it is recommended that further research is carried considering the storage value considering the aggregation of multiple applications and compared to other flexibility options, IRENAS's Electricity Storage Valuation Framework [60] can be used as a guide.

The previous recommendations were formulated considering the thesis works results. However, these proved to be sensitive to the market conditions. Therefore, it is important to understand the key modelling limitations and how can these affect the reached conclusions. One of the most important assumptions of the research was taking the imports and exports as constant for all the scenarios. As explained in Section 2.2, the DA market is coupled and cleared simultaneously for 25 interconnected countries. Therefore, imports, exports, and locational marginal prices can be significantly affected by a change in the generation mix or the addition of storage capacity.

Moreover, the generation and demand of the interconnected countries also play an important role in the Belgian MCPs, and therefore affect the ESS operation scheduling strategy. Even though the formulations of the market clearing problem and the price-maker ESS strategy presented in Section 3.1.2 consider multiple nodes and could solve the optimization representing the coupled market, running the model with that configuration would require the collection of vast amounts of data and greater computational power than the one available for the present study. Therefore, this analysis was excluded from the present study scope.

The simplified import and export assumptions allowed to use the historical Belgian DA market prices as an input for the Baseline scenario modelling. However, given that the import and exports were held constant, the resulting model and the present research findings are more representative of an isolated Belgian DA market case than an interconnected one. This leads to overestimating the price-effect of large-scale ESS and, consequently, the effects of energy storage on the SEW [24]. While the literature recognises the value of storage in decreasing generation costs and integrating larger shares of VRES, it is also widely agreed that interconnections and power exchanges are another important source of flexibility and adequacy and that these are key for the decarbonisation of the European energy system [52]. Consequently, running the current model with the inclusion of interconnections and the consideration of the increasing LVRES penetration in the interconnected counties would be an interesting topic for further research.

Another limitation is related to the DA demand elasticity. Even though literature often assume an inelastic electricity demand, the aggregated demand bids information provided by EPEX SPOT [49] showed an elastic demand for the Belgian DA market. Nevertheless, historical market bids are not freely available and could not be used for calculating the demand elasticity, only market results from the present and previous market day (D and D-1) are publicly shared. As a result, demand behaviour had to be estimated from analysing market results for certain weekdays during the thesis process period and not from data of the modelled days. The previous could lead to the price-effect of storage can being over or underestimated, and therefore so would the magnitude of the difference in SEW. Still, the comparative results are expected to give an accurate indication of the trends and general behaviour of the SEW indicators considering differences in energy mix, storage level, and VRES availability.

Regarding the ESS assumptions, the sensitivity analysis showed that, even though there are differences in the SEW when changing the technical parameters, the conclusions of the analysis hold. However, the effect of the assumed interaction between the storage players was not tested. The used Level-1 strategy would be applicable for assuming inexperienced players or when the strategy from the other players is unknown. Nonetheless, assuming a price-taker operation for large-scale storage is inaccurate as it can even lead to a profit loss, as seen in Section 4. Therefore, a Nash equilibrium modelling would probably be a better representation of the interaction between storage players. In this, the price-maker strategy of each merchant-owned storage is simultaneously optimized, reaching a solution where, given the decisions by all storage players, no player has an incentive to deviate from its chosen strategy [61]. Given that the net revenue of storage operation relies on the difference between the low and high prices, it could be expected that the Nash-Equilibrium solution leads to higher storage revenues, but a smaller welfare benefit for the other market players than the one obtained with the current assumptions. Further research is recommended to explore in detail the effects of storage and market players interaction and its effect on the SEW and VRES integration.

Finally, it is important to keep in mind that the model was run for 24-hour periods. Therefore, the results are based on the daily SEW effects and net revenues of storage systems. Studying a longer modelling period, such as a year, is recommended for further research. Said modelling period could result in differences in the ESS bidding strategies and give further insight into the effects of storage in the wholesale markets by considering the addition of days with various VRES availabilities and demand patterns.

Despite the mentioned limitations, the current research work contributed to the discussion regarding the role of large-scale ESS in the electricity system by indicating the societal effects of its participation in electricity markets and showed how these change in relation to the generation mix, installed storage capacity, and market and meteorological conditions of the operation days. Furthermore, the present thesis considered different players for the addition of storage capacity and, therefore, studied the effect of the interactions between multiple large-scale storage owners. Previous research work mostly considered one monopolist storage system in their analysis [7], [8], [10], [11], [24], [62], or price-taker participation [8], [10], [15]. Additionally, the research process included the development of a model, and corresponding Julia program, which allows studying the integration of multiple price-maker ESS into an auction-based electricity market. This model can be used as a base for further studies by changing the input data to model different markets or storage technologies. Additionally, it could be further developed to integrate interconnections, locational marginal pricing, and more advanced ESS operation strategies.

7 Conclusion

The current work aimed to explore the effects of large-scale BESS integration into the Day-Ahead (DA) market on the SEW under different VRES penetration levels in the Belgian electricity market. To achieve this, a combined market clearing model that included the optimal operation of multiple merchant-owned ESS systems (PHES and BESS) was formulated and programmed. The model was run for scenarios with two different VRES penetration levels and five installed ESS storage capacities, including a no storage scenario.

The results showed that large-scale ESS could have a significant impact for all market participants of the electricity market in comparison to the no storage case by levelling the differences in the on-peak and off-peak MCP and avoiding the use of expensive generation. This results in the redistribution of producers and consumers' wealth in a way that generally benefits the consumer. With the transition to a low-carbon energy system by increasing the VRES participation in the generation mix, ESS systems have the potential of significantly improving the SEW by levelling the extreme maximum and minimum prices caused by the daily cycles of the solar generation.

Furthermore, the research compared the price-taker vs. the price maker ESS bidding strategy and found that the price-maker ESS player's profit maximizing objective does not always align with the optimal solution from the SEW perspective and can lead to limited use of the storage capacity. As a result, and in order to avoid the concentration of market power, distributing the new storage capacity in independently owned ESS would be recommended from the SEW perspective over the concentration of storage capacity in few market players.

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Appendix A. Mathematical formulation of Bilevel Optimization for Price-Maker ESS Strategy and transformation to MILP

1. Bilevel problem

Upper-Level Problem: Maximization of profit storage player

$$\max_{E,b,P_{dis_t},P_{ch_t},O_{dis_t},O_{ch}} \sum_{t=1}^{24} \sum_{n\in N} \lambda_{k,t} \left(Q_{dis_{n,t}} - Q_{ch_{n,t}} \right) \cdot \Delta t$$

s.t.

$$E_{n,t} = E_{n,t-1} + (\eta_{ch_n} \cdot Q_{ch_{n,t-1}} - \eta_{dis_n}/Q_{dis_{n,t-1}}) \cdot \Delta t \qquad \forall t, \forall n$$

$$E_{r_n} \cdot (1 - DoD_n) \le E_{n,t} \le E_{r_n} \qquad \forall t, \forall n$$

$$E_{n,1} = E_{r_n} \cdot SOC_{0_n} \qquad \forall t, \forall n$$

$$E_{n,T} = E_{r_n} \cdot SOC_{0_n} \qquad \forall t, \forall n$$

$$0 \le P_{dis_{n,t}} \le b_{n,t} P_{r_n} \qquad \forall t, \forall n$$

$$0 \le P_{ch_{n,t}} \le (1 - b_{n,t}) P_{r_n} \qquad \forall t, \forall n$$

$$O_{ch_{n,t}} = 3000 \cdot (1 - b_{n,t}) \qquad \forall t, \forall n$$

$$O_{dis_{n,t}} = 0 \cdot b_{n,t} \cdot P_{r_n} \qquad \forall t, \forall n$$

Lower-Level Problem: Market Clearing

$$\max_{Qd_d, Qs_s, Qdis_n, Qch_n\, \delta_k} \sum_{t\in T} \left(\sum_{d\in D} \left(Pd_{d,t} * Qd_{d,t} \right) - \sum_{s\in S} \left(Ps_{s,t} * Qs_{s,t} \right) - \sum_{n\in N} \left(Odis_{n,t} \cdot Qdis_{n,t} \right) + \sum_{n\in N} \left(Och_{n,t} \cdot Qch_{n,t} \right) \right)$$

s.t.

$$\sum_{d\in\varphi_k^d} Qd_{d,t} - \sum_{s\in\varphi_k^s} Qs_{s,t} - \sum_{n\in\varphi_k^n} Qdis_{n,t} + \sum_{n\in\varphi_k^n} Qch_{n,t} - \sum_{l\in\varphi_k^l} B_{k,l}\left(\delta_{k,t} - \delta_{l,t}\right) = 0 \qquad \forall k, \forall t$$

$$Qs_{s,t} \le Msk_{s,t} \qquad \forall s, \forall t$$

$$Qd_{d,t} \le Mdk_{d,t} \qquad \forall d, \forall t$$

$$Qdis_{n,t} \le Pdis_{n,t} \qquad \forall n, \forall t$$

$$Qch_{n,t} \le Pch_{n,t} \qquad \forall n, \forall t$$

$$-TrC_{k,l} - \beta_{k,l}\left(\delta_{k,t} - \delta_{l,t}\right) \le 0 \qquad \forall k, \forall l \in \varphi_k^l, \forall t$$

$$\beta_{k,l}\left(\delta_{k,t} - \delta_{l,t}\right) - TrC_{k,l} \le 0 \qquad \forall k, \forall l \in \varphi_k^l, \forall t$$

$\delta_{k=ref,t} = 0$ $\forall t$

$Qs_{s,t} \geq 0$ $\forall s, \forall t$

$Qd_{d,t} \geq 0$ $\forall d, \forall t$

$Qdis_{n,t} \geq 0$ $\forall n, \forall t$

$Qch_{n,t} \geq 0$ $\forall n, \forall t$

2. Lower problem standard form:

$$\min_{Qd_d, Qs_s, Qdis_n, Qch_n\ \delta_k} \sum_{t \in T} \left(-\sum_{d \in D} (Pd_d * Qd_d) + \sum_{g \in G} (Ps_s * Qs_s) + \sum_{n \in N} (Odis_{n,t} \cdot Qdis_{n,t}) - \sum_{n \in N} (Och_{n,t} \cdot Qch_{n,t}) \right)$$

s.t:

$$\sum_{d \in \varphi_k^d} Qd_s - \sum_{g \in \varphi_k^g} Qs_s - \sum_{N \in \varphi_k^n} Qdis_n + \sum_{n \in \varphi_k^n} Qch_n - \sum_{l \in \varphi_k^l} B_{k,l}(\delta m_k - \delta m_l) = 0\ ; \qquad \lambda_k \quad \forall k$$

$Qs_d - Mgk_g \leq 0\ ; \mu_{1_s}$ $\forall s, \forall t$

$Qd_d - Mdk_d \leq 0\ ; \mu_{2_d}$ $\forall d, \forall t$

$Qdis_n - P_{dis_{n,t}} \leq 0\ ; \mu_{3_n}$ $\forall n, \forall t$

$Qch_n - P_{ch_{n,t}} \leq 0\ ; \mu_{4_n}$ $\forall n, \forall t$

$-TrC_{k,l} - B_{k,l}(\delta_k - \delta_l) \leq 0\ ; \bar{\eta}_{k,l}$ $\forall k, \forall l \in \varphi_{,k}^l, \forall t$

$B_{k,l}(\delta_k - \delta_l) - TrC_{k,l} \leq 0\ ; \underline{\eta}_{k,l}$ $\forall k, \forall l \in \varphi_k^l, \forall t$

$\delta_{k=ref} = 0\ ;$ φ

$-Qs_s \leq 0\ ; \mu_{5_s}$ $\forall s, \forall t$

$-Qd_d \leq 0\ ; \mu_{6_d}$ $\forall d, \forall t$

$-Qdis_n \leq 0\ ; \mu_{7_n}$ $\forall n, \forall t$

$-Qch_n \leq 0\ ; \mu_{8_n}$ $\forall n, \forall t$

3. Dual Lower Problem

$$\max_{\mu_1, \mu_2, \mu_3, \mu_4, \mu_5, \mu_6 \mu_7, \mu_8, \lambda} -\sum_{s \in S} \mu_{1_s} \cdot Msk_s - \sum_{d \in D} \mu_{2_d} \cdot Mdk_d - \sum_{n \in N} \mu_{3_n} * P_{dis_{n,t}} - \sum_{n \in N} \mu_{4_n} * P_{ch_{n,t}} - \sum_{k \in K} \sum_{l \in \varphi_k^l} TrC_{k,l} * (\bar{\eta}_{k,l} + \underline{\eta}_{k,l})$$

s.t:

$$-\lambda_{k:s\in\varphi_k^s} + Ps_s + \mu_{1_s} - \mu_{5_s} = 0 \qquad \forall s, \forall t$$

$$\lambda_{k:d\in\varphi_k^d} - Pd_d + \mu_{2_d} - \mu_{6_d} = 0 \qquad \forall d, \forall t$$

$$-\lambda_{k:n\in\varphi_k^n} + O_{dis_n} + \mu_{3_n} - \mu_{7_n} = 0 \qquad \forall n, \forall t$$

$$\lambda_{k:n\in\varphi_k^n} - O_{ch_n} + \mu_{4_n} - \mu_{8_n} = 0 \qquad \forall n, \forall t$$

$$\sum_{l\in\varphi_k^l} B_{k,l}\left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) = 0 \qquad \forall k\ \forall t$$

$$\sum_{l\in\varphi_k^l} B_{k,l}\left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) + \varphi = 0 \qquad \forall k = 1, \forall t$$

4. Karush Kuhn Tucker (KKT) conditions of Lower Problem:

$$-\lambda_{k:s\in\varphi_k^s} + Ps_s + \mu_{1_s} - \mu_{5_s} = 0 \qquad \forall s\ \ \forall t$$

$$\lambda_{k:d\in\varphi_k^d} - Pd_d + \mu_{2_d} - \mu_{6_d} = 0 \qquad \forall d, \forall t$$

$$-\lambda_{k:N\in\varphi_k^n} + O_{ESS_n} + \mu_{3_n} - \mu_{7_n} = 0 \qquad \forall n, \forall t$$

$$\lambda_{k:n\in\varphi_k^n} - O_{ch_n} + \mu_{4_n} - \mu_{8_n} = 0 \qquad \forall n, \forall t$$

$$\sum_{l\in\varphi_k^l} B_{k,l}\left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) = 0 \qquad \forall k, \forall t$$

$$\sum_{l\in\varphi_k^l} B_{k,l}\left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) + \varphi = 0 \qquad \forall k = 1$$

$$\sum_{d\in\varphi_k^d} Qd_d - \sum_{g\in\varphi_k^g} Qs_s - \sum_{N\in\varphi_k^n} Qdis_n + \sum_{n\in\varphi_k^n} Qch_n - \sum_{l\in\varphi_k^l} B_{k,l}(\delta_k - \delta_l) = 0 \qquad \forall k, \forall t$$

$$\delta m_{k=ref} = 0$$

$$0 \le -Qs_s + Mgk_s \perp \mu_{1_s} \ge 0 \qquad \forall s, \forall t$$

$$0 \le -Qd_d + Mdk_d \perp \mu_{2_d} \ge 0 \qquad \forall d, \forall t$$

$$0 \le -Qdis + P_{dis_{n,t}} \perp \mu_{3_n} \ge 0 \qquad \forall n, \forall t$$

$$0 \le -Qch + P_{ch_{n,t}} \perp \mu_{4_n} \ge 0 \qquad \forall n, \forall t$$

$$0 \le Qg_g \perp \mu_{5_s} \ge 0 \qquad \forall s, \forall t$$

$$0 \le Qd_d \perp \mu_{6_d} \ge 0 \qquad \forall d, \forall t$$

$$0 \le Qdis_n \perp \mu_{7_n} \ge 0 \qquad \forall n, \forall t$$

$$0 \le Qch_n \perp \mu_{8_n} \ge 0 \qquad \forall n, \forall t$$

$$0 \le TrC_{k,l} + B_{k,l}(\delta_k - \delta_l) \perp \bar{\eta}_{k,l} \ge 0 \qquad \forall k, \forall l \in \varphi_k^l, \forall t$$

$$0 \leq -B_{k,l}(\delta_k - \delta_l) + TrC_{k,l} \perp \underline{\eta}_{k,l} \geq 0 \quad \forall k, \forall l \in \varphi_k^l, \forall t$$

5. Resulting MPEC Problem

$$\max_{E,b,P_{dis_t},P_{ch_t},O_{dis_t},O_{ch_t},Qd_d,Qs_s,Qdis_n,Qch_n,\delta_k,\mu_1,\mu_2,\mu_3,\mu_4\mu_5,\mu_6\mu_7,\mu_8,\lambda} \sum_{t=1}^{24} \sum_{n\in N} \lambda_{k,t} \left(Q_{dis_t} - Q_{ch_t}\right) \cdot \Delta t$$

s.t.

$$E_{n,t} = E_{n,t-1} + (\eta_{ch_n} \cdot Q_{ch_{n,t-1}} - \eta_{dis_n}/Q_{dis_{n,t-1}}) \cdot \Delta t \qquad \forall t, \forall n$$

$$E_{r_n} \cdot (1 - DoD_n) \leq E_{n,t} \leq E_{r_n} \qquad \forall t, \forall n$$

$$E_{n,1} = E_{r_n} \cdot SOC_{0_n} \qquad \forall t, \forall n$$

$$E_{n,T} = E_{r_n} \cdot SOC_{0_n} \qquad \forall t, \forall n$$

$$P_{dis_{n,t}} \leq b_{n,t} P_{r_n} \qquad \forall t, \forall n$$

$$P_{ch_{n,t}} \leq (1 - b_{n,t}) P_{r_n} \qquad \forall t, \forall n$$

$$O_{ch_{n,t}} = 3000 \cdot (1 - b_{n,t}) \qquad \forall t, \forall n$$

$$O_{dis_{n,t}} = 0 \cdot b_{n,t} \cdot P_{r_n} \qquad \forall t, \forall n$$

$$-\lambda_{k:s\in\varphi_k^s} + Ps_s + \mu_{1_s} - \mu_{5_s} = 0 \qquad \forall t, \forall s$$

$$\lambda_{k:d\in\varphi_k^d} - Pd_d + \mu_{2_d} - \mu_{6_d} = 0 \qquad \forall t, \forall d$$

$$-\lambda_{k:n\in\varphi_k^n} + O_{dis_n} + \mu_{3_n} - \mu_{7_n} = 0 \qquad \forall n, \forall t$$

$$\lambda_{k:n\in\varphi_k^n} - O_{ch_n} + \mu_{4_n} - \mu_{8_n} = 0 \qquad \forall n, \forall t$$

$$\sum_{l\in\varphi_k^l} B_{k,l} \left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) = 0 \qquad \forall t,, \forall k$$

$$\sum_{l\in\varphi_k^l} B_{k,l} \left(-\lambda_k + \lambda_l - \bar{\eta}_{k,l} + \bar{\eta}_{l,k} + \underline{\eta}_{k,l} - \underline{\eta}_{l,k}\right) + \varphi = 0 \qquad \forall t, \forall k = 1$$

$$\sum_{d\in\varphi_k^d} Qd_d - \sum_{g\in\varphi_k^g} Qg_g - \sum_{N\in\varphi_k^n} Qdis_n + \sum_{n\in\varphi_k^n} Qch_n - \sum_{l\in\varphi_k^l} B_{k,l}(\delta_k - \delta_l) = 0 \qquad \forall t, \forall k$$

$$\delta m_{k=ref} = 0$$

$$0 \leq -Qs_s + Msk_s \perp \mu_{1_g} \geq 0 \qquad \forall t, \forall s$$

$$0 \leq -Qd_d + Mdk_d \perp \mu_{2_d} \geq 0 \qquad \forall t, \forall d$$

$$0 \leq -Qdis + P_{dis_{n,t}} \perp \mu_{3_n} \geq 0 \qquad \forall n, \forall t$$

$0 \leq -Qch + P_{ch_{n,t}} \perp \mu_{4_n} \geq 0 \qquad \forall n, \forall t$

$0 \leq Qg_g \perp \mu_{5_s} \geq 0 \qquad \forall t, \forall s$

$0 \leq Qd_d \perp \mu_{6_d} \geq 0 \qquad \forall t, \forall d$

$0 \leq Qdis_n \perp \mu_{7_n} \geq 0 \qquad \forall n, \forall t$

$0 \leq Qch_n \perp \mu_{8_n} \geq 0 \qquad \forall n, \forall t$

$0 \leq TrC_{k,l} + B_{k,l}(\delta_k - \delta_l) \perp \bar{\eta}_{k,l} \geq 0 \qquad \forall t, \forall k, \forall l \in \varphi_k^l$

$0 \leq -B_{k,l}(\delta_k - \delta_l) + TrC_{k,l} \perp \underline{\eta}_{k,l} \geq 0 \qquad \forall t, \forall k, \forall l \in \varphi_k^l$

6. Linearizing Objective Function

From strong duality:

$$-\sum_{g\in G} \mu_{1_g} * Msk_s - \sum_{d\in D} \mu_{2_d} * Mdk_d - \sum_{n\in N} \mu_{3_n} * P_{dis_{n,t}} - \sum_{n\in N} \mu_{4_n} * P_{ch_{n,t}} - \sum_{k\in K} \sum_{l\in\varphi_k^l} TrC_{k,l} * \left(\bar{\eta}_{k,l} + \underline{\eta}_{k,l}\right)$$
$$= -\sum_{d\in D} (Pd_d * Qd_d) + \sum_{g\in G} (Ps_s * Qs_s) + \sum_{n\in N} \left(Odis_{n,t} \cdot Qdis_{n,t}\right) - \sum_{n\in N} \left(Och_{n,t} \cdot Qch_{n,t}\right)$$

From KKT conditions of lower problem (all multiplied by $Qdis_n$ or Qch_n):

$$-\sum_{n\in N} \lambda_{k:N\in\varphi_k^n} \cdot Qdis_n + \sum_{n\in N} O_{dis_n} \cdot Qdis_n + \sum_{n\in N} \mu_{3_n} \cdot Qdis_n - \sum_{n\in N} \mu_{7_n} \cdot Qdis_n = 0$$

$$\sum_{n\in N} \lambda_{k:N\in\varphi_k^n} \cdot Qch_n - \sum_{n\in N} O_{ch_n} \cdot Qch_n + \sum_{n\in N} \mu_{4_n} \cdot Qch_n - \sum_{n\in N} \mu_{8_n} \cdot Qch_n = 0$$

Recalling complementarity conditions:

$0 \leq -Qdis + P_{dis_{n,t}} \perp \mu_{3_n} \geq 0 \;\rightarrow\; \mu_{3_n} \cdot Qdis = \mu_{3_n} \cdot P_{dis_{n,t}}$

$0 \leq Qdis_n \perp \mu_{7_n} \geq 0 \;\rightarrow\; \mu_{7_n} \cdot Qdis_n = 0 \quad \forall t, \forall n$

$0 \leq -Qch + P_{ch_{n,t}} \perp \mu_{4_n} \geq 0 \;\rightarrow\; \mu_{4_n} \cdot Qch = \mu_{4_n} \cdot P_{ch_{n,t}}$

$0 \leq Qch_n \perp \mu_{8_n} \geq 0 \;\rightarrow\; \mu_{8_n} \cdot Qch_n = 0 \quad \forall t, \forall n$

Obtaining:

$$-\sum_{n\in N} \lambda_{k:N\in\varphi_k^n} \cdot Qdis_n + \sum_{n\in N} O_{dis_n} \cdot Qdis_n + \sum_{n\in N} \mu_{3_n} \cdot P_{dis_{n,t}} = 0$$

$$\sum_{n\in N} O_{dis_n} \cdot Qdis_n = \sum_{n\in N} \lambda_{k:N\in\varphi_k^n} \cdot Qdis_n - \sum_{n\in N} \mu_{3_n} \cdot P_{dis_{n,t}}$$

$$\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot Qch_n-\sum_{n\in N}O_{ch_n}\cdot Qch_n+\sum_{n\in N}\mu_{4_n}\cdot P_{ch_{n,t}}\ =0$$

$$\sum_{n\in N}O_{ch_n}\cdot Qch_n=\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot Qch_n+\sum_{n\in N}\mu_{4_n}\cdot P_{ch_{n,t}}$$

Substituting in strong duality:

$$\begin{aligned}-\sum_{g\in G}\mu_{1_s}\cdot Msk_s-\sum_{d\in D}\mu_{2_d}\cdot Mdk_d\ -\sum_{n\in N}\mu_{3_n}\cdot P_{dis_{n,t}}\ -\sum_{n\in N}\mu_{4_n}*P_{ch_{n,t}}-\sum_{k\in K}\sum_{l\in\varphi_k^l}TrC_{k,l}\cdot\left(\bar{\eta}_{k,l}+\underline{\eta}_{k,l}\right)\\ =\ -\sum_{d\in D}\left(Pd_{d,t}*Qd_{d,t}\right)+\sum_{s\in S}\left(Ps_{s,t}*Qs_{s,t}\right)+\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot Qdis_n-\sum_{n\in N}\mu_{3_n}\cdot P_{dis_{n,t}}\\ -\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot Qch_n-\sum_{n\in N}\mu_{4_n}\cdot P_{ch_{n,t}}\end{aligned}$$

Final linear optimization objective:

$$\begin{aligned}\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}Qdis_n-\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot Qch_n\\ =-\sum_{g\in G}\mu_{1_s}\cdot Msk_s-\sum_{d\in D}\mu_{2_d}\cdot Mdk_d\ \cancel{-\sum_{n\in N}\mu_{3_n}\cdot P_{dis_{n,t}}}\ \cancel{-\sum_{n\in N}\mu_{4_n}*P_{ch_{n,t}}}\\ -\sum_{k\in K}\sum_{l\in\varphi_k^l}TrC_{k,l}\cdot\left(\bar{\eta}_{k,l}+\underline{\eta}_{k,l}\right)\ +\sum_{d\in D}\left(Pd_{d,t}*Qd_{d,t}\right)-\sum_{s\in S}\left(Ps_{s,t}*Qs_{s,t}\right)\\ +\cancel{\sum_{n\in N}\mu_{3_n}\cdot P_{dis_{n,t}}}\cancel{+\sum_{n\in N}\mu_{4_n}\cdot P_{ch_{n,t}}}\end{aligned}$$

$$\begin{aligned}\boldsymbol{\sum_{n\in N}\lambda_{k:N\in\varphi_k^n}\cdot(Qdis_n-Qch_n)=\ -\sum_{g\in G}\mu_{1_s}\cdot Msk_s-\sum_{d\in D}\mu_{2_d}\cdot Mdk_d\ -\sum_{k\in K}\sum_{l\in\varphi_k^l}TrC_{k,l}\cdot\left(\bar{\eta}_{k,l}+\underline{\eta}_{k,l}\right)}\\ \boldsymbol{+\sum_{d\in D}\left(Pd_{d,t}\cdot Qd_{d,t}\right)-\sum_{s\in S}\left(Ps_{s,t}\cdot Qs_{s,t}\right)}\end{aligned}$$

Appendix B. Belgium Model Input Data

The following files are attached as part of Appendix:

1. Appendix B. Belgium Model Input Data. xlsx

Description: The excel file contains the Belgium electricity market data collected and used to generate the input files used to model the Baseline and LVRES scenarios in the created Julia program.

Appendix C. Price-taker SEW results

Table C.1 shows the KPIs obtained by modelling the scenarios using the price-taker approach. The difference in SEW, Consumer Surplus, Producer Surplus, and ESS Revenue (ΔSEW, ΔCS, ΔPS, and ΔESS R respectively) were calculated in relation to the No Storage Level.

Table C.1. KPIs for price-taker modelling. Differences (Δ) expressed in relation to No Storage level. All quantities are in thousands of € per day.

	Baseline				LVRES			
Storage Level	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**	**ΔSEW**	**ΔCS**	**ΔPS**	**ΔESS R**
January								
No Storage	-	-	-	-	-	-	-	-
Existing PHES	48.25	1,293.24	-1,175.15	-69.83	-10.98	426.22	-366.01	-71.19
Low	45.82	1,317.26	-1,185.59	-85.85	-12.54	368.70	-305.87	-75.37
Medium	15.09	1,726.28	-1,534.78	-176.41	-34.48	147.48	-26.70	-155.26
High	-114.57	-1,137.24	1,672.81	-650.13	-102.00	-504.56	801.49	-398.93
March								
No Storage	-	-	-	-	-	-	-	-
Existing PHES	-66.87	-117.85	159.28	-108.31	-34.83	-285.02	290.87	-40.68
Low	-72.17	-76.84	123.63	-118.96	-37.92	-285.02	290.87	-43.78
Medium	-105.56	-296.49	378.02	-187.09	-50.30	-285.02	290.87	-56.15
High	-191.56	-1,134.30	1,364.75	-422.00	-68.28	126.42	-87.26	-107.45
June								
No Storage	-	-	-	-	-	-	-	-
Existing PHES	-5.94	766.73	-691.98	-80.69	-115.11	-466.97	695.43	-343.57
Low	-14.42	822.01	-705.93	-130.50	-135.52	-451.14	728.57	-412.94
Medium	-65.69	144.70	32.00	-242.39	-254.50	-2,463.78	3,084.35	-875.07
High	-177.04	-405.43	735.96	-507.57	-1,572.16	-34,547.57	40,590.19	-7,614.78
September								
No Storage	-	-	-	-	-	-	-	-
Existing PHES	-177.96	-649.88	774.46	-302.53	-4,747.66	52,812.24	-47,122.93	-10,436.97
Low	-193.68	-712.23	846.48	-327.93	-5,395.32	52,782.27	-47,089.59	-11,087.99
Medium	-256.07	-1,530.09	1,802.49	-528.47	-7,997.44	53,785.46	-47,923.91	-13,858.99
High	-424.72	-3,840.85	4,542.97	-1,126.84	-11,306.69	54,113.75	-48,145.86	-17,274.58