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Xian He, Erik Delarue, William D'haeseleer and Jean-Michel Glachant

EUROPEAN UNIVERSITY INSTITUTE, FLORENCE
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For further information
Loyola de Palacio Energy Policy Chair
Email contact: yannick.perez@eui.eu
Robert Schuman Centre for Advanced Studies
European University Institute
Via delle Fontanelle, 19
I-50016 San Domenico di Fiesole (FI)
Fax: +39055 4685755

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Abstract

Electricity storage is considered a valuable source of flexibility whose applications cover the whole electricity value chain. However, most of the existing evaluation methods for electricity storage are conceived for only one specific use of the storage, which often leads to the conclusion that the investment on storage does not pay off. We think that the value of storage cannot be properly estimated without taking into account the possibility of aggregating the services that storage can offer to different actors. In this paper, we propose a new business model that allows aggregating multiple revenue streams of electricity storage in a systematic way. The main idea of the business model is to coordinate a series of auctions in which the right to utilize the storage unit is auctioned in different time horizons. The model consists of an optimization module and a coordination mechanism. The former simulates the optimal strategy of a certain actor using the available storage capacities in a certain auction, while the latter ensures non-conflicting uses of storage by actors in different auctions. The functioning of the model is demonstrated by a case study. The results show that a storage unit can achieve a higher return on investment in the manner proposed in the business model.

Keywords

Electricity storage; Business model; Optimization

1. Introduction

The electricity storage technologies can provide multiple services in the generation, transmission, and distribution, as well as in the end-user activities. The function of electricity storage lies in a bi-directional transformation process: first, electricity is transformed into a storable form of energy, and second, the stored energy is transformed rapidly into electric energy in case of need. So, the electricity storage technology is not an energy generation means in strict sense, but a valuable flexibility resource adjunctive to all the resources in the power system, which can help achieve a higher asset utilization rate and contributing to the reliability of the power system, especially in the scenarios of massive intermittent renewable energy penetration.

Many studies have been undertaken to evaluate the benefits of electricity storage. Some focus on the arbitrage value of electricity storage in the spot market of electricity [1-4]. Walawalkar et al. also estimates the value of electricity storage in providing regulation services in the market environment [4]. Other studies look into the use of electricity storage at transmission or distribution level [5-8]. The end-user applications are often studied in the scope of distributed energy storage system. The economics of coupling the electricity storage to wind farms is investigated in [9-12]. An overlap of the two former categories of studies is presented in [13-14] which deal with the transmission-related benefits of combining wind and storage. However, by focusing on only one specific application of electricity storage, most of the analyses mentioned above do not show profitability of investment in storage in the current context. As indicated in [15-17], one sole benefit does not allow the cost recovery of storage facilities in most cases. These references point out that the combination of services could lead to a better perspective for the development of storage. The societal value of storage should be properly recognized and accounted for in the cost recovery of the storage facilities. While engineers continue to make efforts to lower down the capital cost of electricity storage technologies, economists have began to search for ways to increase the revenue of electricity storage, through the aggregation of the benefits of storage.

To date, a relatively small number of works have been carried out in this direction. In [15] the idea of a combination of services is set out, together with the principles of combination, which are the operational and technical compatibilities. In [13] and [16], several combination options are tested for a case study. Although these studies provide valuable visions of combined benefit of storage, they feature several weaknesses. First, the combination options are case-specific and therefore hard to generalize. This would create difficulty for a general and non-discriminatory regulation on storage to emerge. Second, for a certain combination option, an allocation of storage resource for different services is defined beforehand instead of being the result of an optimization. The common approach for such allocation is to designate a certain period of time during which the storage is dedicated only to one service. As a result, the use of storage at a certain time is still exclusive, which implies in fact a "division" of storage resource for different services along the time. Third, the combination options studied in these analyses might be specific to the electricity landscape in the US, where the integrated actors can easily merge several applications of storage that fall in different spheres of activities. However, the viability of some combination options would be questioned in Europe, where the electricity sector is unbundled and deregulated. In Europe, the challenge of aggregating the values of storage is more related to the questions 1) how the regulated actors and deregulated actors can share the use of one storage unit, and 2) how the decentralized use of storage by different actors can be effectively coordinated. As an answer to these questions, we propose a business model that enables us to systematically aggregate the values of storage in the deregulated electricity sectors.

The new business model distinguishes from the existing methods in that it does not predefine the service that the storage is supposed to offer, nor does it reserve the capacities of the storage in advance for a certain service. The model consists of arranging a series of auctions in which the right to utilize the storage unit is auctioned in different time horizons. The aggregation of values of storage is achieved by superposing the utilization profiles of storage resulting from the auctions chain. A non-conflicting usage of the storage unit is ensured by communicating the utilization profiles resulting from the previous auctions to the actors in the next auction, who are required to respect the utilization profiles previously established when elaborating their own strategy on the use of storage.

The paper is structured as follows: section 2 introduces the concept of the business model. The mathematic formulation of the model is presented in Section 3. In Section 4, we demonstrate the functioning of the model by a case study, together with a discussion of the key results. Section 5 concludes the paper.

2. Concept of the business model

The core of the business model lies in organizing a series of auctions to sell the available power and energy capacities of the storage unit among different actors. The auctions are taking place in sequential time horizons. For example, we can introduce in the first place a week-ahead auction, which is followed by a day-ahead auction, and in the last place an hour-ahead auction can be carried out. In each auction, the underlying product is the right to explore the remaining "capacities of storage"[1] during the auctioned period. Different actors will decide upon their strategy to use the storage according to their own objective function, be it maximizing the profit, minimizing the cost, or minimizing the risk, etc. In principle, all actors are asked to keep the energy balance over the auctioned period, which means that the sum of power injected into the storage should be equal to the sum of the power withdrawn from the storage unit at the end of the auctioned period. This energy balance requirement demonstrates the principle that the storage facility is auctioned as a flexibility resource, but not as an energy generation resource. In this way, each actor will use the energy that he himself charges into the storage unit, so there will be no conflict of interest between actors in different auctions.

The bid the actors submit consists of two parts: a utilization profile of the storage unit over the underlying period and one sole price for the desired utilization profile. The bidder who offers the highest price (thus who attaches the most value to use the storage unit in that horizon of time) will win the auction[2]. Note that the utilization profile submitted will imply real energy charge and discharge at the maturity time and does not stand for the reservation of the charge and discharge capacity. The utilization profile defined as such presents the property of being able to be aggregated. As illustrated by the formula below, the final charge or discharge of the storage unit at a certain time is the result of several charge or discharge actions that different actors (actor A, B, C) have decided upon a different time horizon.

$$charge_t = charge_t^A - discharge_t^B + charge_t^C$$

This way, the use of the storage unit by different actors will result in only one final charge or discharge action, while the value of the storage unit will be the sum of the values that each actor attaches to the desired utilization profile. Hence, the aggregation of values of storage is achieved.

As a storage unit has limited charge, discharge and energy storage capacities, a coordination mechanism is needed to ensure the feasibility of aggregating several utilization profiles. The organizer

[1] The notion of "capacities of storage" refers to the charge/discharge capacities (in MW) and energy storage capacity (in MWh) of an electricity storage unit.

[2] The bidder who participates in the auction can be one single actor or be an aggregator who aggregates the desired utilization profiles of several actors. Therefore, the joint optimization of the use of storage by several actors within one auction is allowed in the presented model, as long as they submit one profile and one price. But as the optimization of utilization profile is an external part of the business model, for the sake of simplicity, we will only simulate simple optimization process for single actors in the case study in order to put more emphasis on the auction chaining process.

of the auction (who can be the owner of the storage) will communicate the retained utilization profiles of the previous auctions to the actors in the subsequent auction. All the actors in this auction are asked to submit their desired utilization profile and the corresponding price while respecting the utilization profiles previously established. In other words, the utilization profiles retained in the previous auctions are firm, and add to the constraints to be obeyed in the next auction. Each auction will end up with a utilization profile that extracts the highest value from the remaining capacities of storage.

The table below gives a schematic illustration of the conduction of the auctions.

Table 1. Conduction of the auctions

Time horizon	Constraints to obey	Energy balance clearing**	Bid	
			Utilization profile	Price
Week-ahead	Physical constraints of storage	At the end of week	Profile_week	Value_week
Day-ahead	Physical constraints of storage	At the end of day	Profile_day	Value_day
	Profile_week			
xhour-ahead*	Physical constraints of storage	At the end of day	Profile_xhour	Value_xhour
	Profile_week			
	Profile_day			
Hour-ahead	Physical constraints of storage	At the end of day	Profile_hour	Value_hour
	Profile_week			
	Profile_day			
	Profile_xhour			

*x can be 12, 8 or 4, or any hour if we wish to introduce an auction with the gate closure time x-hour ahead of real time delivery.

**refers to the time when the energy level in the storage should return to the previously established value.

3. Model description

As an application of the model, a case study is formulated in this section. In the case study, we consider an auction chain composed of three sequential auctions. The first auction is the week-ahead auction, in which we study how a supplier would use the storage to lower down the supply cost. The second auction is the day-ahead auction, in which we simulate the strategy of a trader who wants to use storage to capture arbitrage profit on the spot market. The third auction introduced is the hour-ahead auction, in which we consider the case of a TSO who would like to use the remaining capacities of storage to provide regulating energy in the real time. Other possibilities of the auction chain composition can be simulated in future studies.

Note that the choice of the actor (and his desired service) in this study is just for the purpose of illustration. It suffices to replace the objective function by that of another actor if we want to simulate how other actors elaborate their bids in the same auction.

In the remainder of the section, the developed optimization and coordination algorithms are presented for each auction. Mixed-Integer Linear Programming (MILP), and Mixed-Integer Quadratically Constrained Programming (MIQCP) models are used to solve the optimization problem for different actors. The model is implemented partly in Matlab and partly in GAMS (using the Matlab/GAMS link) and is solved using the Cplex 10.0 solver.

3.1 Week-Ahead Auction

In the week-ahead auction, a supplier can use storage to lower his supply cost by avoiding the use of expensive peak units, and by economizing the part-load cost and start-up cost of power plants (which would have occurred in order to follow the time-varying load without the aid of storage). The use of storage will be optimized over the whole week. The objective function of the supplier is a single cost function to be minimized, with ‘i’ being the set of power plants (index i) and t’ the set of time periods (index t’), corresponding to 168 hours of the week:

$$minimize \quad obj = \sum_{i} \sum_{t'=1}^{168} \left(CF_{i,t'} + CU_{i,t'} \right) \tag{1}$$

with obj : total cost of electricity generation with storage [€]

$CF_{i,t'}$: fuel cost of plant i, hour t’ of the week [€]

$CU_{i,t'}$: start-up cost of plant i, hour t’ of the week [€]

A stepwise cost function of a power plant is introduced to account for the production efficiency at different output levels. The minimum up-and down-time constraints are taken into account. The ramp rate is not considered here because it is hardly binding on an hourly basis. We refer to [20] for the formulation of cost functions and constraints.

The constraint that enforces the satisfaction of the demand during all hours is written as:

$$\forall t' \in T' : d_{t'} = \sum_{i} g_{i,t'} - charge^{w}_{t'} + discharge^{w}_{t'} \tag{2}$$

with $d_{t'}$: electricity demand during hour t’ of the week [MW][3]

$g_{i,t'}$: electricity generation of plant i during hour t’ of the week [MW]

$charge^{w}_{t'}$: charging power (storing energy) during hour t’ of the week in the week-ahead auction [MW]

$discharge^{w}_{t'}$: discharging power (releasing energy from the storage) during hour t’ of the week in the week-ahead auction [MW]

Supposing that there is no auction prior to the week-ahead auction, the exploration of the storage unit is confined by the physical ratings of the storage unit:

$$\forall t' \in T' : \quad 0 \le charge^{w}_{t'} \le SC \tag{3}$$

$$\forall t' \in T' : \quad 0 \le discharge^{w}_{t'} \le SD \tag{4}$$

$$\forall t' \in T' : \quad 0 \le E^{w}_{t'} \le SE \tag{5}$$

with $E^{w}_{t'}$: energy level in the storage after the charge or discharge action of storage unit at the end of hour t’ of the week [MWh]

SC: maximum charge capacity of the storage unit [MW]

SD: maximum discharge capacity of the storage unit [MW]

SE: maximum energy capacity of the storage unit [MWh]

Equation (6) traces the energy level in the storage. There is an efficiency loss during the charge phase as well as during the discharge phase. The charge efficiency and the discharge efficiency are both considered equal to the square root of the round trip efficiency.

[3] Throughout the paper, we assume constant power within one hour, be it power produced, consumed, charged into the storage or discharged from the storage.

$$\forall t' \in T': \quad E^w_{t'} = E^w_{t'-1} + charge^w_{t'} \cdot \mu \cdot T^w - discharge^w_{t'} \cdot \frac{1}{\mu} \cdot T^w \tag{6}$$

with μ: charge or discharge efficiency of the storage unit [-]
T^w: time period length considered in the week-ahead auction, equal to 1 [h]

Equation (7) enforces that the energy level at the end of the week should be equal to the energy level at the beginning of the week, which is the initial energy stored. We assume that the initial energy is set to the level that allows equal duration of charge and discharge at maximum capacity[4].

$$E^w_{168} = E_{initial} = \frac{SD}{SD+SC} \cdot SE \tag{7}$$

with $E_{initial}$: energy level in the storage at the beginning of the week [MWh]

After the closure of the week-ahead auction, the retained utilization profile for the 168 hours of the week is transformed into the corresponding action at the hour t of the day j, and will be entered as firm constraints to respect in the day-ahead auction. Hence, $charge^w_{t'}$, $discharge^w_{t'}$, and $E^w_{t'}$ (with the set of time periods T' {1, 2, …, 168}, with index t') are transformed to $charge^w_{j,t}$, $discharge^w_{j,t}$, and $E^w_{j,t}$, respectively, with J the set of days {1, 2, …, 7} (index j) and T the set of hours {1, 2, …, 24} (index t).

3.2 Day-Ahead Auction

In the day-ahead auction, we simulate the case of a trader who uses storage to do arbitrage in the day-ahead spot market. In order to understand the link between the week-ahead auction and the day-ahead auction, we will introduce first the notions of net action and remaining capacities, which are key to the coordination mechanism. Next, the optimization algorithm of the trader is presented.

3.2.1 Net Action and Remaining Capacities

The actions (charge or discharge) desired by different actors in different auctions can add up or cancel out. It is important to keep in mind that the energy level change is related only to the aggregated action on storage, because the efficiency loss is applied to the net energy charged into or discharged from the storage unit at a certain time. Here we introduce the notion of net action which stands for the actual action implemented on the storage unit at a certain time. Mathematically, the net action is defined as the difference between the implemented charge action and discharge action, as shown in (8) [5].

$$netaction^w_{j,t} = charge^w_{j,t} - discharge^w_{j,t} \qquad t \in (1,2,...,24) \tag{8}$$

By this definition, a positive net action implies a charge action, while a negative net action implies a discharge action. As we will see later in this section, the net action after the day-ahead auction will further include the day-ahead actions on the storage.

The net action will educe another important notion which is the remaining capacities of storage. They set the boundaries of allowed actions in the underlined auction:

$$RC^d_{j,t} = SC - netaction^w_{j,t} \tag{9}$$

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[4] This assumption is intended to give the bidders more liberty of actions at the beginning of the auction period. As a comparison, setting the initial energy level at the minimum or maximum energy capacity of the storage unit will prevent the bidders from taking any discharging or charging actions respectively, during the first periods.

[5] Simultaneous charge and discharge actions are not allowed technically, so at least one of the charge and discharge actions in equation (8) takes the value of zero.

$$RD_{j,t}^{d} = SD + netaction_{j,t}^{w} \quad (10)$$

with $RC_{j,t}^{d}$: remaining charge capacity for hour t of day j in the day-ahead auction [MW]

$RD_{j,t}^{d}$: remaining discharge capacity for hour t of day j in the day-ahead auction [MW]

It is stressed that that the "remaining capacities" defined as such are in a commercial sense[6]. For example, if the winner in the week-ahead auction wishes to discharge the storage at a certain time, (9) will allow the day-ahead bidder to charge the storage (in a commercial sense) at a rate higher than the physical rating, as long as the sum of the week-ahead discharge action and the day-ahead charge action is lower than the maximum capacity rating of the storage unit. Likewise, if the week-ahead actor wishes to charge the storage at a certain time, bidders in the next round of auction would have possibilities to discharge beyond the physical discharge capacity. The storage unit, given its unique capacity of being able to operate in two directions, can perfectly accommodate the offsetting actions as described above, and can generate values for different actors with a limited power rating.

3.2.2 Day-Ahead Optimization Considering Market Resilience

In the existing studies about the arbitrage value of storage, the spot market price of electricity is generally viewed as an exogenous variable which is independent from the operation of storage. However, this method would lead to an overestimation of storage's value. In fact, by storing at low prices and discharging at high prices, the storage may reduce the inter-temporal price spread, leading to less arbitrage value than anticipated. In our analysis, we will incorporate the market resilience factor, which indicates the price sensitivity to an increase in offer or demand in a certain market, into the optimization algorithm of the trader. As indicated by the objective function below, the trader would expect the impact of his charge or discharge action on the market price and would take this impact into account when deciding the optimal arbitrage strategy.

The objective function of the trader is written as:

$$\forall j \in J: \quad maximize \quad profit = \sum_{t=1}^{24} \begin{pmatrix} discharge_{j,t}^{d} \cdot T^{d} \cdot (P_{j,t} + discharge_{j,t}^{d} \cdot T^{d} \cdot resil) \\ -charge_{j,t}^{d} \cdot T^{d} \cdot (P_{j,t} - charge_{j,t}^{d} \cdot T^{d} \cdot resil) \end{pmatrix} \quad (11)$$

with $charge_{j,t}^{d}$: charging power (storing energy) during hour t of day j in the day-ahead auction [MW]

$discharge_{j,t}^{d}$: discharging power (releasing energy from the storage) during hour t of day j in the day-ahead auction [MW]

resil: resilience factor indicating the price change due to an increase in supply or demand on the market [€/MWh/MWh]. It is by definition negative.

profit : maximum arbitrage profit [€]

$P_{j,t}$: day-ahead spot price during hour t of day j [€/MWh]

T^{d}: time period length considered in the day-ahead auction, equal to 1 [h]

As stated before, the desired utilization of the storage unit in the day-ahead auction should respect the utilization profile established in the precedent auction. The allowed actions in the day-ahead auction are bounded by the remaining charge and discharge capacities after the week-ahead use of storage:

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[6] The model conceived in the paper does not take into account the impact of possible network constraints on the "technically feasible" charging or discharging capacities of storage. Indeed, an offsetting action that is economically interesting for one actor may induce a network congestion that would cause additional cost to the power system. However, the current electricity markets are arranged such that it is not the task of individual market participant to deal with network constraint resulting from the commercial exchanges between them; the network operator will try to resolve congestion or any demand-supply imbalances in a central manner, in order to respect as much as possible the market results. That is why in the present model, the "remaining capacities" of storage are defined in commercial sense.

$$\forall j \in J\ ,\ \forall t \in T:\ \ 0 \le charge^{d}_{j,t} \le RC^{d}_{j,t} \tag{12}$$

$$\forall j \in J\ ,\ \forall t \in T:\ \ 0 \le discharge^{d}_{j,t} \le RD^{d}_{j,t} \tag{13}$$

The net action after the day-ahead use of storage is written as:

$$\forall j \in J,\ \forall t \in T,:\ \ netaction^{d}_{j,t} = charge^{w}_{j,t} + charge^{d}_{j,t} - discharge^{w}_{j,t} - discharge^{d}_{j,t} \tag{14}$$

Formula (15) gives the inter-temporal energy level changes in the storage due to the aggregated action after the week-ahead and day-ahead auctions:

$$\forall j \in J\ ,\ \forall t \in T, t \neq 1:\ \ E^{d}_{j,t} = E^{d}_{j,t-1} + \left(netaction^{d}_{j,t} \cdot y^{d}_{j,t}\right) \cdot \mu \cdot T^{d} + \left[netaction^{d}_{j,t} \cdot (1 - y^{d}_{j,t})\right] \cdot \frac{1}{\mu} \cdot T^{d} \tag{15}$$

with $E^{d}_{j,t}$: energy level in the storage after the charge or discharge action at the end of hour t of day j in the day-ahead auction [MWh]

$netaction^{d}_{j,t}$: net action on the storage unit during hour t of day j after the day-ahead use of storage [MW]

$y^{d}_{j,t}$: binary indicating whether the net action after the day-ahead use of storage is charging the storage unit or not: 1 if yes, 0 if not.

For the first hour of the day, the $E^{d}_{j,t-1}$ in (15) is replaced by the corresponding energy level at the beginning of the day which is established in the week-ahead auction.

Formula (16) sets the minimum and maximum limits of the energy level after the day-ahead use of the storage. (17) enforces that for each day j, the energy level at the last hour should be equal to the energy level established in the week-ahead auction. It means that the day-ahead use of storage should result in zero net energy change at the end of day.

$$\forall j \in J\ ,\ \forall t \in T:\ \ 0 \le E^{d}_{j,t} \le SE \tag{16}$$

$$\forall j \in J:\ \ E^{d}_{j,24} = E^{w}_{j,24} \tag{17}$$

3.3 Hour-Ahead Auction

According to the current market arrangements, all the commercial power exchanges are closed at least one hour ahead of real time delivery of power. The transmission system operator (TSO) could still use the remaining storage capacities to provide regulating energy in real time. This conduct will not generate a conflict with the commercial use of storage, and will make economic sense for the power system. On the one hand, the energy cost to activate conventional regulation reserve could be avoided if the required regulation energy is provided by storage. On the other hand, if the storage is proven to be able to systematically supply a certain amount of regulation energy when required, the total reserve requirement ascribed to conventional means could be reduced without compromising the reliability of the system, and more capacity could be released for energy production. Above all, from a technical point of view, the storage technologies generally outperform other conventional means of generation to prevent frequency excursions in case of system contingencies, because of very short reaction time and high ramp rates of storage technologies [18].

In our simulation, the system operator will maximize the use of remaining storage capacities to provide regulating energy instead of resorting to other less flexible production plants. Due to the physical law of frequency regulation, the charge or discharge action on storage depends solely on the direction of the regulation required. The system operator can decide to activate the storage unit or not to provide the required regulation. By using the storage capacities on real time basis, there is inevitably an energy balance deviation at the end of one hour or at the end of the day. The previously established utilization profiles might not be respected. In order to avoid such situations from occuring, in the hour-ahead model we enforce that the TSO would explore the storage only during the first 23 hours of the day. The last hour is reserved for the final adjustment action. A verification procedure will be launched during the first 23 hours to ensure that the hour-ahead use of storage will not disturb the previously established utilization profiles, and that there is enough offsetting capacity during the last hour of the day to bring the energy level back to the targeted value.

3.3.1 Estimation of Hour-Ahead Use of Storage –Two Approaches

In reality, the TSO disposes of complicated simulation software such as Eurostag [19] to simulate the short term and transient dynamic of the power system and can have a quite accurate estimation of the use of storage in real time. Our paper does not endeavor to replicate the same analysis as those complicated commercial softwares, but is aimed at demonstrating how the hour-ahead use of storage can be incorporated into the business model. To this purpose, we develop two approaches that would set the maximum and minimum boundaries of the hour-ahead use of storage.

First Approach: Perfect Foresight

The first approach assumes full foresight over the regulation direction and volume during the whole day. The objective function of the TSO is to maximize the use of storage to provide regulation energy during the first 23 hours of a day:

$$\forall j \in J, \forall t \in (1,2,...,23): \quad maximize \;\; obj = \sum_{q=1}^{4}\left(charge_{j,t,q}^{h} + discharge_{j,t,q}^{h}\right) \qquad (18)$$

Note that a new set Q is introduced (with index q), for the time periods within set T. In this case, every hour t is split into 4 quarters Q = {1, 2, 3, 4}.

The available storage capacities for the hour-ahead auction are given by the equations (19) - (20). Recall that the net action on the storage unit after the day-ahead auction is given by (14).

$$\forall j \in J \;,\; \forall t \in (1,2,...,23): \;\; RC_{j,t}^{h} = SC - netaction_{j,t}^{d} \qquad (19)$$

$$\forall j \in J \;,\; \forall t \in (1,2,...,23): \;\; RD_{j,t}^{h} = SD + netaction_{j,t}^{d} \qquad (20)$$

with $RC_{j,t}^{h}$: remaining charge capacity for hour t of day j in the hour-ahead auction [MW]
$RD_{j,t}^{h}$: remaining discharge capacity for hour t of day j in the hour-ahead auction [MW]

The charge or discharge action implemented by the TSO within one hour should be less than the remaining charge or discharge capacity, as well as the downward or upward regulation energy requirement:

$$\begin{aligned} &\forall j \in J, \; \forall t \in (1,2,...23), \;\; \forall q \in Q: \\ &0 \le discharge_{j,t,q}^{h} \le RD_{j,t}^{h} \\ &0 \le discharge_{j,t,q}^{h} \le regulation_{j,t,q} \cdot b_{j,t,q} \end{aligned} \qquad (21)$$

$$\begin{aligned}&\forall j \in J,\ \forall t \in (1,2,...23),\ \forall q \in Q:\\&0 \le charge^{h}_{j,t,q} \le RC^{h}_{j,t}\\&0 \le charge^{h}_{j,t,q} \le regulation_{j,t,q} \cdot (b_{j,t,q} - 1)\end{aligned} \tag{22}$$

with $b_{j,t,q}$: binary parameter (input data) indicating whether an upward regulation is taking place at quarter q of hour t, day j; if upward regulation, 0 if downward regulation.

$charge^{h}_{j,t,q}$: charging power (storing energy) during quarter q of hour t, day j in the hour-ahead auction [MW]

$discharge^{h}_{j,t,q}$: discharging power (releasing energy from the storage) during quarter q of hour t, day j in the hour-ahead auction [MW]

$regulation_{j,t,q}$: system's requirement of the upward or downward regulation; positive if upward regulation, negative if downward regulation [MW]

Equation (23) calculates the net action after the hour-ahead use of storage.

$$\begin{aligned}&\forall j \in J,\ \forall t \in (1,2,...23),\ \forall q \in Q:\\&netaction^{h}_{j,t,q} = \left(charge^{w}_{j,t} + charge^{d}_{j,t} + charge^{h}_{j,t,q}\right) -\\&\qquad \left(discharge^{w}_{j,t} + discharge^{d}_{j,t} + discharge^{h}_{j,t,q}\right)\end{aligned} \tag{23}$$

Equation (24) traces the energy level after the hour-ahead use of storage.

$\forall j \in J,\ \forall t \in (1,2,...23),\ \forall q \in Q,\ q \neq 1:$

$$E^{h}_{j,t,q} = E^{h}_{j,t,q-1} + \left(netaction^{h}_{j,t,q} \cdot y^{h}_{j,t,q}\right) \cdot \mu \cdot T^{h} + \left(netaction^{h}_{j,t,q} \cdot (1 - y^{h}_{j,t,q})\right) \cdot \frac{1}{\mu} \cdot T^{h} \tag{24}$$

with T^{h}: time period length considered in the hour-ahead auction, equal to 1/4 [h]

For the first quarter of the hour, the $E^{h}_{j,t,q-1}$ in (24) should be replaced with the corresponding energy level at the beginning of the hour which is established in the previous auctions.

Formula (25) counts the net energy deviation at the end of each quarter. This variable is created for the verification procedure.

$$\forall j \in J,\ \forall t \in (1,2,...23),\ \forall q \in Q:\ \ \sigma_{j,t,q} = E^{h}_{j,t,q} - E^{d}_{j,t} \tag{25}$$

with $\sigma_{j,t,q}$: net energy level shift at the end of quarter q, hour t of day j because of the hour-ahead use of storage [MWh]

Apart from the constraints listed above, we also need to ensure that the hour-ahead actions on the storage will not infringe the utilization profiles established in the previous auctions. The perfect foresight assumption implies that the TSO knows all the opportunities of offsetting regulation actions in the following hours. Hence, we only need to ensure that the energy level at any time remains within the technical limitations, with constraint (26), and that there is sufficient offsetting capacity during the last hour of the day to correct the energy deviation at the end of the 23rd hour, as enforced by (27).

$$\forall j \in J,\ \forall t \in (1,2,...23),\ \forall q \in Q:\ \ 0 \le E^{h}_{j,t,q} \le SE \tag{26}$$

$$\forall j \in J: -RC^{h}_{j,24} \le \sigma_{j,23,4} \le RD^{h}_{j,24} \tag{27}$$

Second Approach: No Foresight

The second approach estimates the use of storage with the assumption that the system operator has no knowledge of the regulation requirement on the following hours. In this case, the decision whether to activate the storage to provide regulation energy at a certain time is made while considering that there will be no offsetting actions during the following hours. The objective function is to maximize the use of storage at each time step, as described by (28). The same constraints (19)-(25) are enforced.

$$\forall j \in J,\ \forall t \in (1,2,...23),\ \ \forall q \in Q:$$
$$total\_use = \sum_{j=1}^{7}\sum_{t=1}^{23}\sum_{q=1}^{4}\left(charge_{j,t,q}^{h} + discharge_{j,t,q}^{h}\right) \tag{28}$$

with *total_use*: total use of storage in the hour-ahead auction

However, the verification procedure is different under the no-foresight assumption. The verification is carried out for each quarter according to the time sequence. At a certain time step, (29) verifies if there is sufficient offsetting capacity during all the following hours to compensate the energy deviation caused by the hour-ahead use of storage. If not, the storage will not be activated to provide the regulation energy.

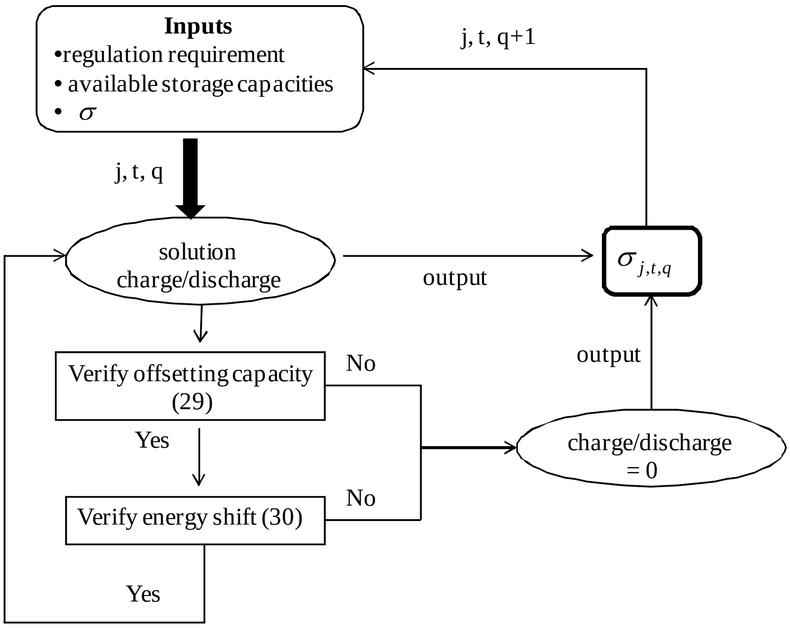
$$\forall j \in J, \forall t \in (1,2,...,23), \forall k \in (t+1, t+2,...,24),\ \ \forall q \in Q:$$
$$-\sum_{k=t+1}^{24} RC_{j,k}^{h} \le \sigma_{j,t,q} \le \sum_{k=t+1}^{24} RD_{j,k}^{h} \tag{29}$$

In addition, we also need to ensure that the energy level change following the hour-ahead use of storage will not shift the energy level out of the maximum and minimum limits for all the following hours. Otherwise, the storage will not be activated to provide the regulation energy. The following constraints are created to this aim:

$$\begin{aligned}
&\forall j \in J,\ \forall t \in (1,2,...23),\ \ \forall q \in Q: \\
&0 \le \sigma_{j,t,q} + E_{j,t}^{d} \le SE \\
&0 \le \sigma_{j,t,q} + E_{j,t+1}^{d} \le SE \\
&... \\
&0 \le \sigma_{j,t,q} + E_{j,24}^{d} \le SE
\end{aligned} \tag{30}$$

This verification procedure is carried out for each quarter according to the time sequence, as illustrated by Figure 1. The results obtained will be the decided charging/discharging action at each time step, as well as the accumulated energy deviation ($\sigma_{j,t,q}$) at the end of this time step. These results will be entered as inputs in the verification procedure of the next quarter.

Figure 1. Verification procedure under the no-foresight assumption



The results calculated under these two assumptions should set the maximum and minimum boundaries of the use of storage to provide regulation energy.

4. Case Study

This section demonstrates the functioning of the business model in a case study. First the input data for each of the auction simulated are described. Second, the simulation results are presented and analyzed.

4.1 Simulation Set Up

The technical parameters of the storage unit in study are presented in Table 2. The storage unit features different charge and discharge capacities. It can fill the energy reservoir at maximum charge rate within 6 hours, and can withdraw all the stored energy within 3 hours at maximum discharge rate. Such set up is intended to highlight the fact that in many cases, the storage unit can be dimensioned to have different charge and discharge rates, which may lead to better economic performance[7].

Table 2. Storage unit characteristics

storage unit	SC	SD	SE	μ_{charge}	$\mu_{discharge}$
	MW	MW	MWh	%	%
	200	400	1200	90	90

SC: maximum charge capacity of the storage unit [MW]
SD: maximum discharge capacity of the storage unit [MW]
SE: maximum energy storage capacity of the storage unit [MWh]
μ: storage conversion efficiency [-]

7 An intuitive evidence is that, as low prices in spot market generally last much longer than peak prices, it makes economic sense to have low charge rate but high discharge rate to achieve higher profit.

In the week-ahead auction, the supplier is supposed to possess a portfolio of base-load, medium-load and peak-load generation units, with a total generation capacity of 1740 MW. We refer to [20] as the source of data. The load pattern is derived from the actual Belgium load [21].

The simulations are carried out for the fourth week of 2007 as a demonstration of the functioning of the business model.

In the day-ahead auction, the Belpex spot prices of the fourth week of 2007 [22] are used in the simulation. The resilience factor is set to be -0.01, which is a reasonable value according to the information provided by [23].

In the hour-ahead auction, the Belgium regulation prices and volumes during the second week of 2007 [21] are used for simulation.

4.2 Simulation Results

In this section, the simulations results for the three auctions are presented and analyzed.

4.2.1 Week-Ahead Auction

In the week-ahead auction, the supplier will first estimate the supply cost without storage. As shown by Figure 2, the coal plant and the peaking units are the main forces to follow the load variations, resulting in high fuel costs and operating at lower part-load efficiencies.

Figure 2. Electricity generation without storage

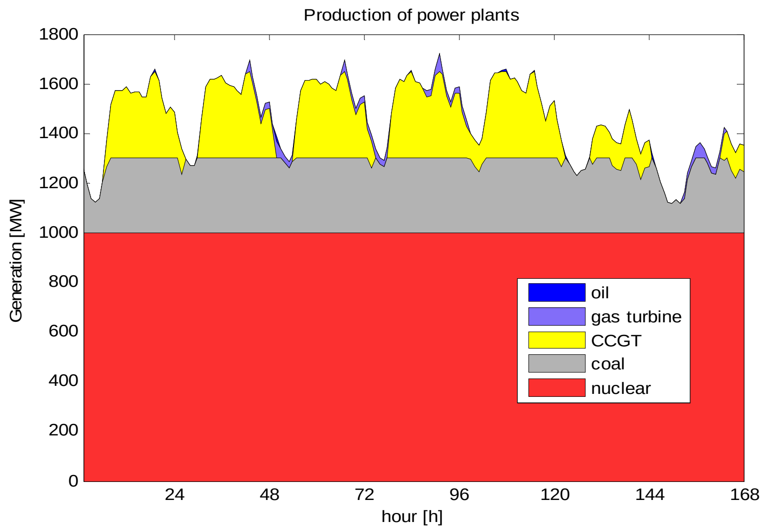


Figure 3 illustrates that, with the help of the storage unit, the supplier can minimize the use of expensive peak-load unit and largely avoid part-load losses. Figure 4 demonstrates the desired utilization profile of storage during the underlying week. The value that the supplier attaches to this utilization profile can be considered as the difference between the total cost of meeting the demand without storage and that with storage. Since the storage is used for load leveling purposes, the week-ahead use of storage will not necessarily imply a charge or discharge action to the maximum capacity of the storage unit.

Figure 3. Electricity generation with storage

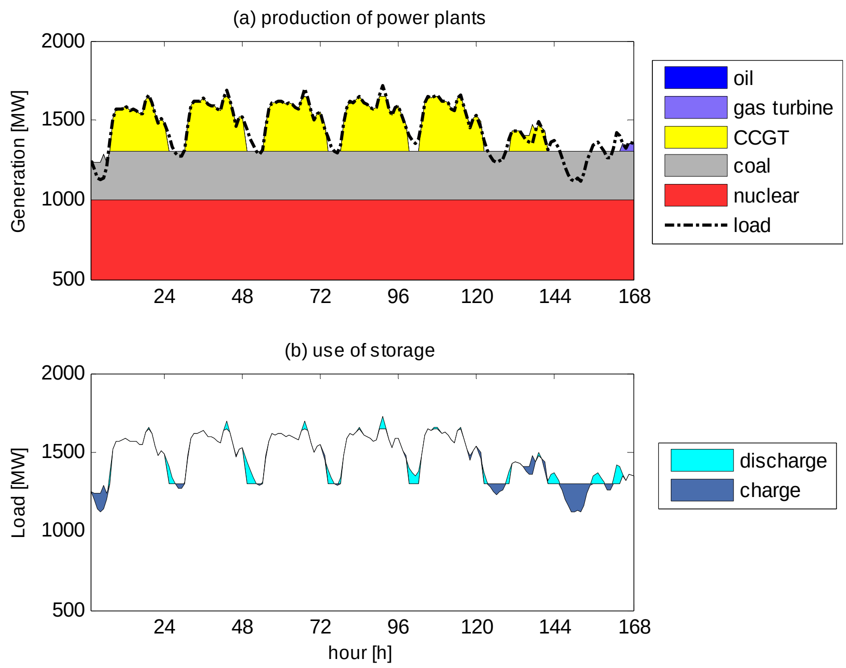
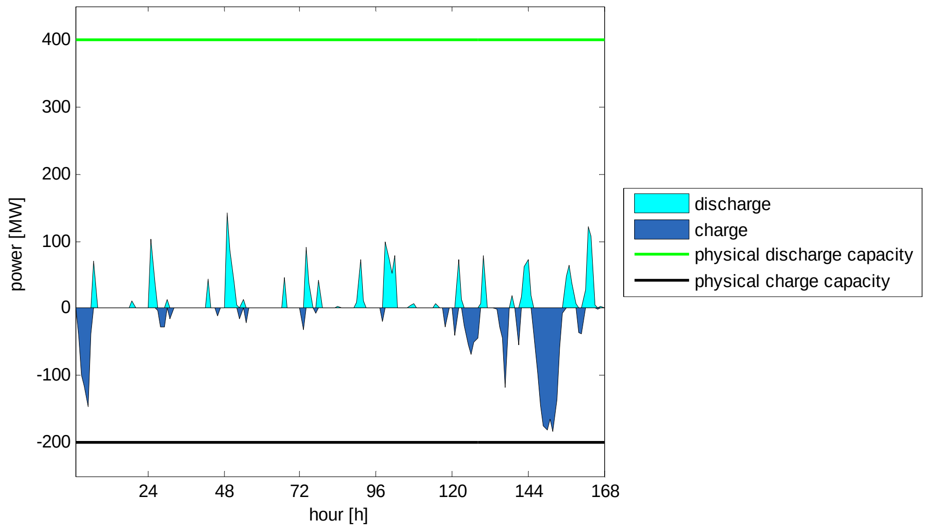


Figure 4. Week-ahead actions on storage

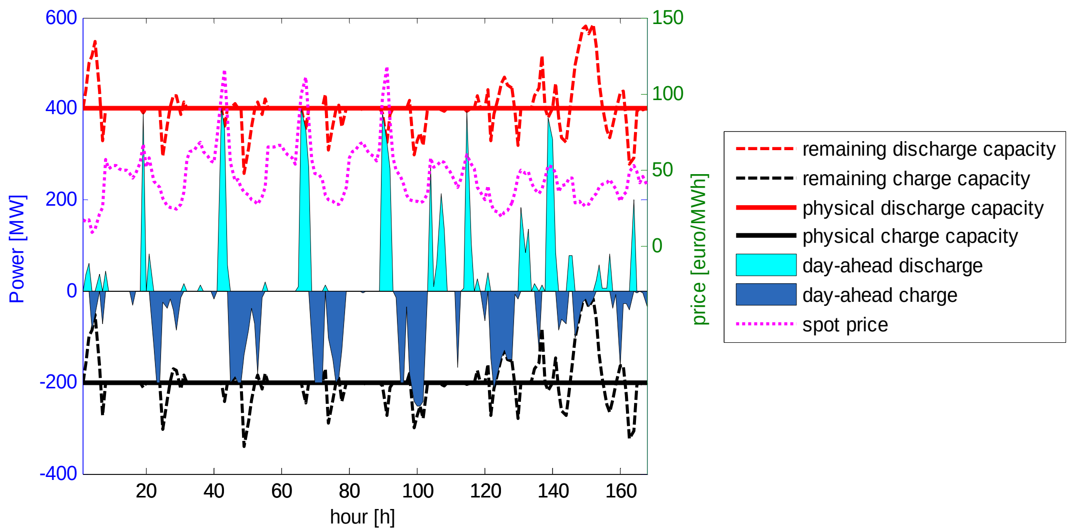


4.2.2 Day-Ahead Auction

In the day-ahead auction, the trader will optimize the use of remaining capacities of the storage unit to make arbitrage profit in the spot market. Figure 5 depicts the allowed actions in the day-ahead auction after the week-ahead use of storage. As one can note, the allowed actions can go beyond the physical power rating of the storage, because the week-ahead actions on storage create more room for the counteracting actions in the subsequent auction.

The case study results show that the week-ahead use of storage only occasionally impedes the trader to charge or discharge at the maximum capacity in the day-ahead action, and this constraint is very limited. On the contrary, during some hours, for instance at the beginning of the fifth day, the week-ahead charge actions on the storage allow for extra discharge capacity in the day-ahead auction. When this period happens to coincide with high prices in the day-ahead spot market, the trader can benefit from the week-ahead use of storage by selling more energy than the physical discharge capacity of storage. Overall, it turns out that the week-ahead use of storage has very little effect in reducing the potential value of day-ahead use of the storage. However, one should note that this finding depends, to a great extent, on the obtained utilization profile established in this specific week-ahead auction.

Figure 5. Day-ahead charge and discharge actions, together with the allowed actions in day-ahead auction. Dashed curves depict the remaining charge and discharge capacities after the week-ahead use of storage. Full lines present the physical maximum charge and discharge capacity of the storage unit. The electricity spot price is presented by the dotted line.



The day-ahead charge and discharge program presented in Figure 5 represent the utilization profile of storage that maximizes the arbitrage profit of the trader in the spot market. The arbitrage profit can be considered as the value that the trader attaches to the corresponding utilization profile. We find that the market resilience has a considerable impact on the optimal strategy, as well as on the arbitrage value of the storage. If no market resilience is taken into account, the arbitrage value of the storage tends to be overestimated by nearly 20% in the same case setting.

Figure 6 presents the aggregated charge/discharge action after the week-ahead and the day-ahead auction. The aggregated actions will ensure that the energy level at the end of the day is equal to the value established in the week-ahead auction, as can be seen in Figure 7.

Figure 6. Aggregated action of week-ahead and day-ahead auction. The aggregated actions are limited by the physical maximum charge and discharge capacities of the storage unit.

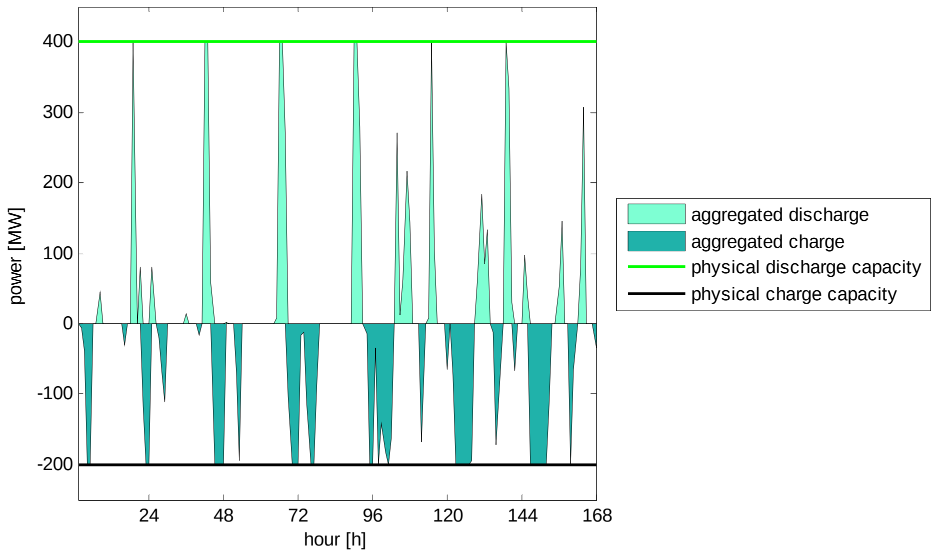
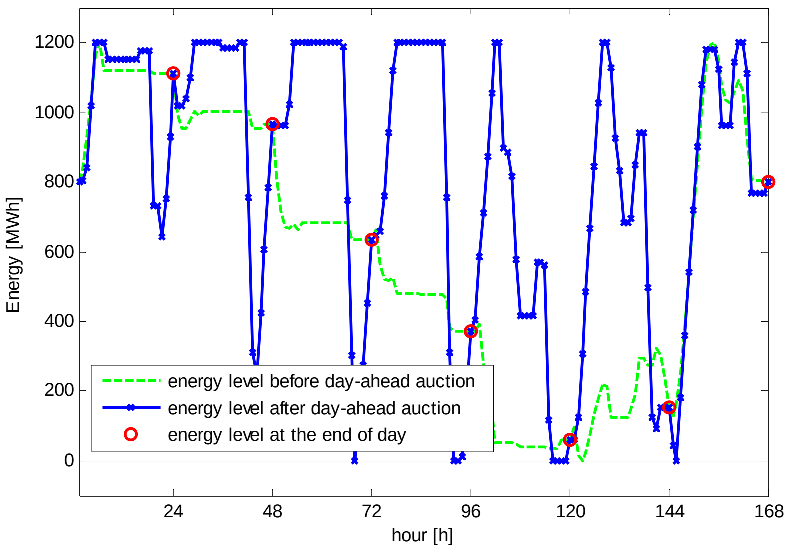


Figure 7 shows that all the actions taken in the day-ahead auction will result in a net energy level change of zero at the end of the day. The storage unit is used as a pure flexibility resource.

Figure 7. Aggregated energy level after week-ahead and day-ahead auction



4.2.3 Hour-Ahead Auction

In the hour-ahead auction, we simulate the use of the remaining storage capacities by the TSO to provide regulation energy within one hour. The figures presented hereinafter correspond to the case where we assume perfect foresight on the regulation requirement by the TSO.

Figure 8 depicts the allowed actions in the hour-ahead auction after the two previous auctions. According to the simulation results under the perfect foresight assumption, the storage is able to supply regulation energy for 67% of time when a certain regulation (upwards or downwards) is required. Given the small volume of regulation power required at each step of 15 minutes (generally between +/- 150 MW), when the storage unit is able to supply regulation energy, it can, for the most of time, meet the total regulation requirement of the system. Under the no-foresight assumption, the availability of storage to provide regulation energy is reduced to 48%. These results show that, without reserving storage capacities on purpose for the supply of regulation energy, the storage unit is still able to provide an important amount of regulation energy in real time. This potential should be recognized and is worth further reflection, as it suggests that the storage unit, by supplying the regulation energy with residual capacities after commercial trading, could eventually replace a certain amount of firm regulation reserve in the power system.

Figure 8. Hour-ahead charge and discharge actions, together with allowed actions in the hour-ahead auction. Dashed curves depict the remaining charge and discharge capacities after the week-ahead and day-ahead use of storage. Full lines present the physical maximum charge and discharge capacity of the storage unit.

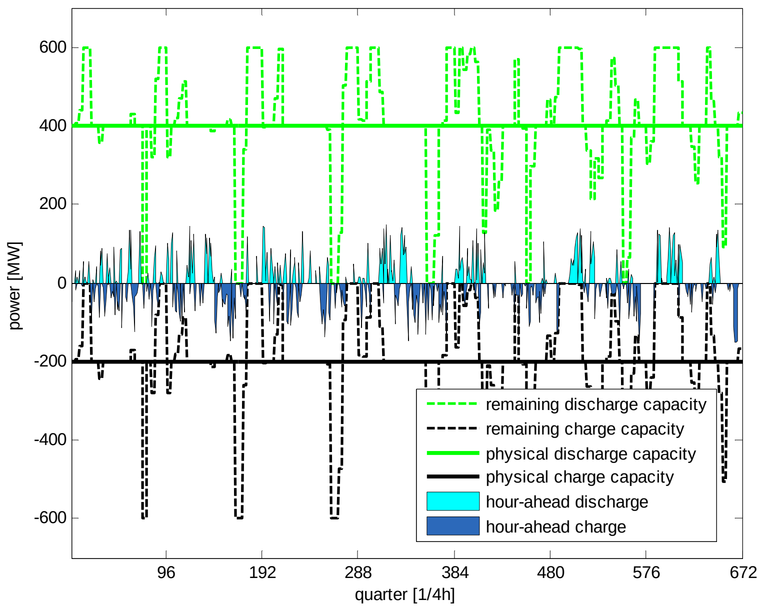


Figure 9 (a) shows the hour-ahead actions which are oscillating on small time step as compared to the week- or day-ahead utilization profile. The hour-ahead utilization profile is then superposed on the aggregated week- and day-ahead use of storage, giving the aggregated utilization profile after the three auctions. The aggregated actions always lay within the physical power rating of the storage unit, as shown in panel (b).

Figure 9. Aggregated of week-, day- and hour-ahead actions

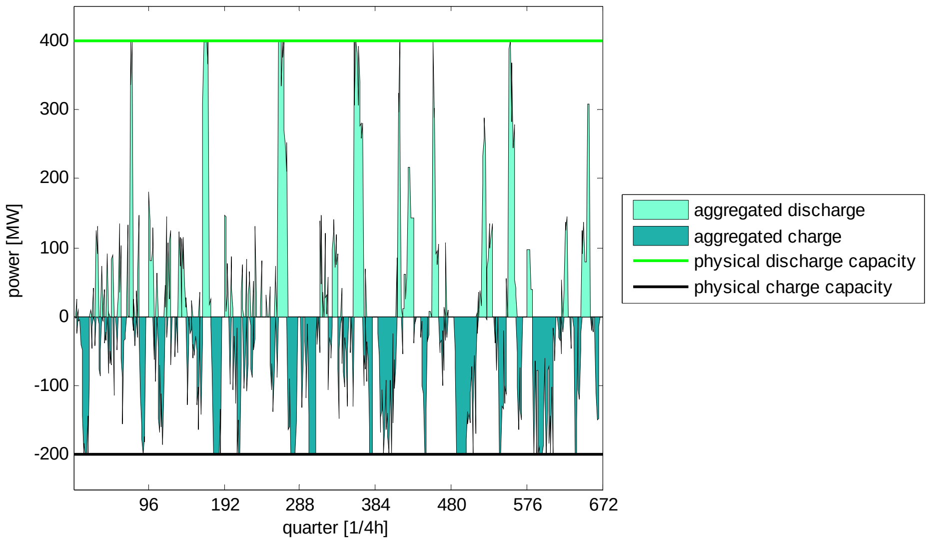
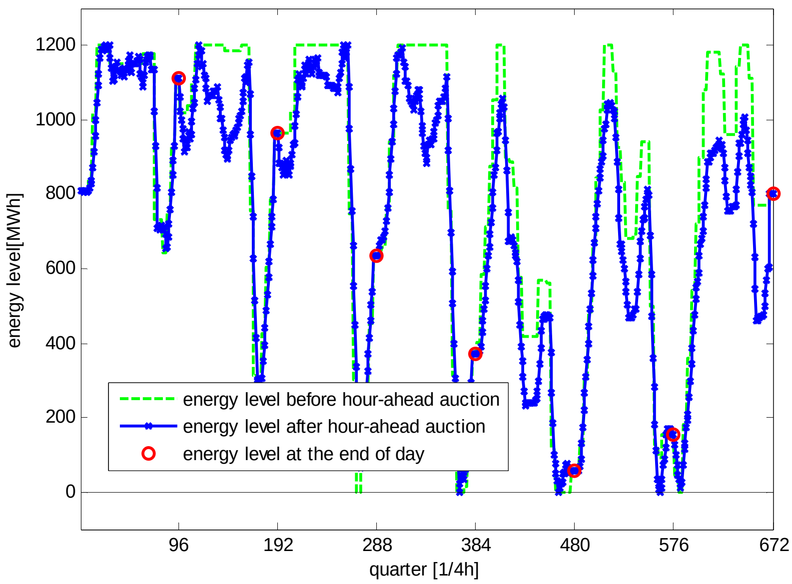


Figure 10 displays aggregated energy levels in the storage after the hour-ahead auctions. The hour-ahead use of storage to provide regulation energy is translated into the small oscillations on the energy level. But the energy level at the end of the day always returns to its due value because of the final adjustment action.

Figure 10. Aggregated energy level after the hour-ahead auction

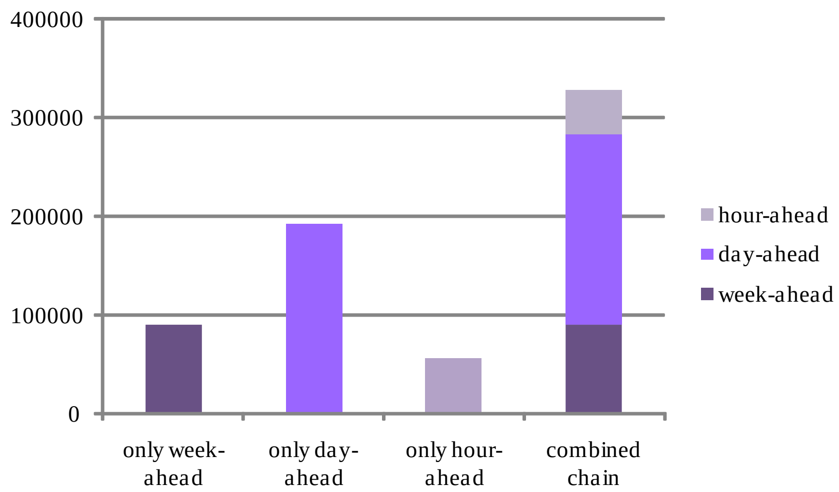


4.3 Aggregated Value Versus Single Value

Figure 11 demonstrates the single value of storage if it is used only by one of the three actors, as opposed to the aggregated value of storage following the auction chain. The monetary unit of value is euro. Recall that the simulations are undertaken for the fourth week of 2007. The hour-ahead value of storage is calculated by applying the regulation energy prices to the volume of regulation energy supplied by the storage[8]. The hour-ahead value presented in Figure 11 corresponds to the perfect foresight assumption. Under the no foresight assumption, this value is about 26% less.

As explained before, the week-ahead use of storage interferes little with the day-ahead use of storage in the case study. In fact, we find that the day-ahead value in the auction chain is even slightly higher than in the case of only day-ahead use of storage. It is explained by the fact that the week-ahead use of storage sometimes makes it possible for the day-ahead user to charge/discharge at capacity higher than the physical power rating. If the storage unit is only dedicated for regulation service, it can supply the regulation energy for around 90% of time both under the perfect foresight and the no foresight assumption. As presented before, the availability of storage for supplying regulation energy is reduced to 50~60% when the use of storage is integrated in the auction chain. But the monetary benefit of using storage exclusively for regulation is not much higher than that in the auction chain, as illustrated by the third and fourth columns in Figure 11. This is because using storage to supply upward and downward regulation entails the cash flows that would compensate each other. According to the simulation results, it is obvious that the aggregated value is much more important than any single value of storage. However, the exact amount of storage's value in each auction depends essentially on the case set up and the input data. The numerical results should therefore be interpreted with caution.

Figure 11. Aggregated value versus single value



5. Discussion and Conclusions

This paper presents a new business model which enables us to aggregate the values of storage in the liberalized electric sector. The core idea of the model lies in organizing an auction chain in which the right to use available capacities of storage is auctioned among different actors. The aggregation of values is achieved superposing the utilization profiles resulting from the chaining auctions. The model proves that it is technically possible to coordinate the use of the storage unit by different actors. The simulation results show that a storage unit can better recover its investment cost by aggregating the value of storage to different actors/services in the manner described in this business model.

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[8] As the TSO incurs cost while activating upward regulation and revenue while activating downward regulation, the value of storage is the difference between the avoided cost and missed revenue.

The coordination algorithm proposed in the model is a generic one and is able to coordinate any utilization profiles without the need to know the underlined service. So the model is ready to simulate more case studies on other applications of storage. More importantly, the generic coordination algorithm is crucial to introduce sufficient and fair competitions among all actors in each auction.

The business model represents an attempt to solve the current investment puzzle of electricity storage units. The economic viability of electricity storage technologies have been long sought, but never achieved in general sense. One important reason is the lack of a proper mechanism which allows the investor to capture the overall value of storage by providing multiple services to the power system. The efforts to aggregate several revenue streams of storage often encounter the regulatory obstacles which forbid the exchange of information between different actors, especially between the regulated actors and deregulated actors. In the proposed business model, the information about the use of storage is resumed in the utilization profile resulting from the auction, and is shared among all the actors in the next auction as a common constraint to obey. On top of that, a market rule is applied to select the winner in an auction.

In the case study, we have shown how a TSO can use the remaining capacities of storage after the closure of commercial exchanges in order to provide regulation energy in the real time. This conduct seems to be consistent with the current regulation that prevents the regulated actors to touch the commercial activities. In this model, the TSO neither takes ownership over the storage unit (which is generally not allowed by the regulation in Europe), nor interferes with the commercial use of storage. We consider it as a viable way to allow aggregating the “deregulated” and “regulated” values of storage. Still, we believe that the regulation plays the key role in the development of electricity storage. The lack of specific regulation for storage would lead to high investment uncertainties, whilst a regulation that fails to recognize the value of storage for the whole system would constitute a barrier for the deployment of storage in the power system. Once the storage is recognized as a “system” resource, as it actually is, we have reasons to believe that the cost of storage should be recovered by both the “deregulated” values and “regulated” values. Hence, the challenge for the policymakers and regulators is to design appropriate mechanisms to coordinate the use of storage with credible signals and without bias to specific actors. The business model proposed in the paper could add to the reflections on this issue.

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Authors contacts:

Xian He

Ingénieur Doctorant

EDF - EDF R&D

EFESE

1 Avenue du Général de Gaulle

92141 Clamart

Email: xian.he@edf.fr

Erik Delarue

University of Leuven (K.U.Leuven)

Department of Mechanical Engineering

Division Applied Mechanics and Energy Conversion

Celestijnenlaan 300A - post box 2421

B-3001 Leuven (Heverlee)

Email: erik.delarue@mech.kuleuven.be

William D’haeseleer

University of Leuven (K.U.Leuven) Energy Institute

TME branch (Applied Mechanics and Energy Conversion)

Celestijnenlaan 300A box 2421

B-3001 Heverlee

Email : william.dhaeseleer@mech.kuleuven.be

Jean-Michel Glachant

Director of the Florence School of Regulation and of the Loyola de Palacio Chair

European University Institute, RSCAS

Villa Malafrasca

Via Boccaccio, 151

I-50014 San Domenico di Fiesole (FI)

Email jean-michel.glachant@eui.eu

European University Institute
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