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Business Model for Aggregating the Value of Storage

By Xian He and Erik Delarue

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Summary

Storage is considered as a valuable source of flexibility in the power systems nowadays which are faced with various challenges such as accommodating intermittent renewable energy, distributed generation, as well as coordinating with electricity markets where actors make their decisions in an independent way. Electricity storage units, by decoupling the generation and the consumption of electric energy, can offer multiple services to different actors in both regulated (transmission and distribution) and deregulated (generation and commercialization) sectors. However, most of the existing methods of storage evaluation are conceived for one specific use of storage, which lead often to the conclusion that the investment cost of storage is not able to be recovered by rending the service in study. We think that the value of storage cannot be appropriately estimated without taking into account the possibility of aggregating the different services that storage can offer to different actors. We propose thus a business model in which the right to utilize one storage unit is auctioned among all actors in different time horizons. The model distinguishes from other existing methods in that it does not predefine the service that the storage is supposed to offer, nor reserve the capacity of the storage in advance for a certain service. The actor that attaches the most value to use the storage will have the right to explore the available power and energy capacity of the storage unit. And a non-conflicting usage of the storage unit is ensured by communicating the utilization profile of the actor in the previous auction to the actors in the next auction, who will continue to explore the remaining capacities of the storage unit in a manner that the utilization profile established in the previous auction is respected.

The report is structured as follows. In section I the objective of the model is stated. Section II gives a brief description of the conception of the model. In section III we present the mathematic formulation of the model. We demonstrate the mechanism to construct five chaining auctions at different time horizon. In each auction, we simulate the optimization process for a specific actor. In section IV, some key results obtained from the case studies are discussed. Section V concludes.

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I. Objective of the model

The primary objective of the model is to investigate whether it is technically possible to aggregate the value of one electricity storage unit to different actors in the current deregulated electric system. In the second place, we are interested to know if this business model allows cost recovery of storage unit, and how the cost recovery is sensitive to the different storage technologies, storage configurations as well as to regulation changes.

II. Description of the model

The model consists in a series of auctions to sell the available power and energy capacity of the storage unit among different actors. The auctions are taking place in sequential time horizons. For example, the week-ahead auction is prior to the day-ahead auction, which is again prior to the hour-ahead auction. In each auction, the underlying product is the right to explore the remaining storage capacities (which refer to the charge/discharge capacities and energy storage capacities, same in the rest of paper) during the auctioned period. In the week-ahead auction for instance, every actor tries to decide his optimal operation strategy of the storage unit for each hour during the coming week under the physical constraints of the storage. Each actor may have his own objective function attached to the use of storage, be it maximizing the profit, minimizing the cost, or minimizing the risk, etc. In principal, all actors are asked to bring the energy level in the storage back to its initial value at the beginning of the period, because the storage facility is auctioned as a flexibility resource, but not an energy generating resource. However, this constraint can be relaxed for the auctions organized at short horizons, e.g. several hours or one hour-ahead auctions, due to the technical difficulty to ensure the energy balance within a short period of exploration.

The bid consists in two parts: a utilization profile of the storage unit during the underlying period and one sole price for the desired utilization profile. Note that the utilization profile submitted will imply real energy charge and discharge at the maturity time in commercial sense 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 can be split into several charge or discharge actions that different actors (actor A, B, C) decide in different time horizon.

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

In this way, the use of the storage unit by different actors will result in only one final charge or discharge action, but the value of the storage unit will be the sum of the value that each actor attaches to the desired action on the storage unit. The aggregation of the value of storage for different actors or services is achieved.

We assume that 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. The organizer of the auction, which can be the owner of the storage, will communicate the retained utilization profile in this auction to the actors in the next round auction closer to real time. All the actors are asked to submit their desired utilization profile and corresponding price while respecting the utilization profile established in the previous auction as well as the physical constraints of the storage unit.

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 we wish to simulate an intraday auction.
**refer to the time when the energy level in the storage should return to its initial value of the auctioned period.

Mixed-integer linear programming (MILP) model and linear programming (LP) model 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.

III. Model outline

At each auction, every actor will optimize his profit or cost function using the remaining storage capacities (both the charge/discharge capacity and energy capacity) resulting from the last round of auction. In this section, the outline of the model is formulated by setting a specific case for each auction. We have simulated five auctions at different time horizon to the real time charge/discharge action.

(a) The first auction is the week-ahead auction of the utilization profile of the storage unit. In this auction, we carry out a case study of a supplier who wants to use the storage to lowering down the supply cost.

(b) The second auction is the day-ahead auction. In this auction, we simulate the strategy of a trader who wants to use storage to capture arbitrage profit on spot market.

(c) The third auction is an intra-day auction just after the closure of day-ahead spot market. In this auction, we simulate the use of storage by the TSO to reduce the congestion cost if the commercial contracts closed after the day-ahead spot market are not totally feasible due to the network constraints.

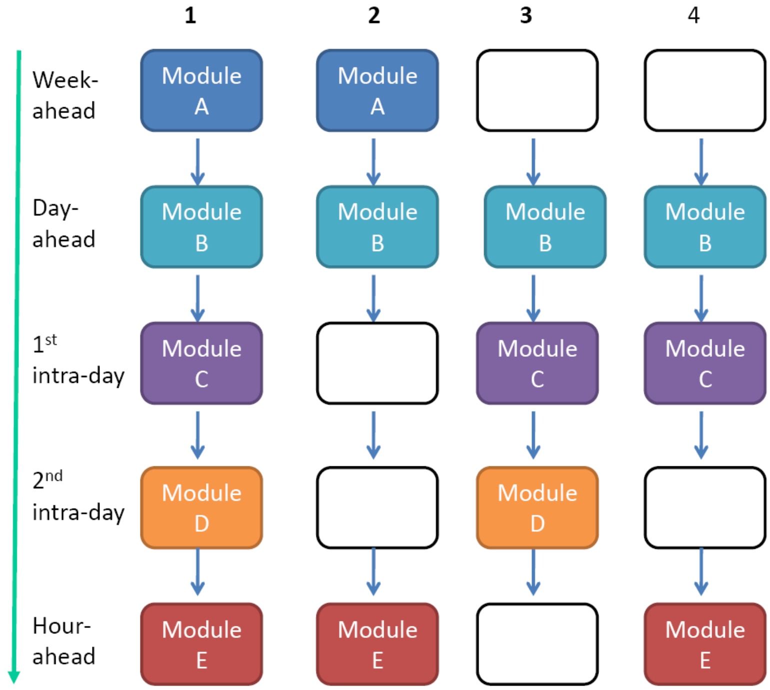
(d) The fourth auction is another intra-day auction closer to the real time dispatch. We simulate the case of a wind producer who is financially responsible for the wind forecast errors. The wind producer may use storage to reduce his imbalance cost when he has more accurate forecast of wind speed for the next day.

(e) The fifth auction is the hour-ahead auction where we consider the case of a TSO who would like to use storage to provide regulating energy in the real time.

The choice of the actor in study of each auction is just for illustration purpose. 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 rest of the section, the formulation of the five modules of auctions is presented by featuring the specific case mentioned above.

Figure1. Possible combinations of auctions



Main symbols

Set	
i	Set of power plant
j	Set of days
l	Set of lines
n	Set of nodes
t	Set of hours of a day
q	Intervals of the hour, i.e.,15 minutes in the case study
Parameters	
$capline_l$	Capacity limit of a line [MW]
$coef^{up}$	Coefficient applied to the production cost increase during the re-dispatch phase [-]
$coef^{down}$	Coefficient applied to the production cost decrease during the re-dispatch phase [-]
$C_{i,n}^{p0}$	Average fuel cost at minimum output of plant i at node n [€/ MWh]
$C_{i,n}^{p1}$	Marginal fuel cost at first part of maximum output of plant i at node n [€/ MWh]
$C_{i,n}^{p2}$	Marginal fuel cost at second part of maximum output of plant i at node n [€/ MWh]
$C_{i,n}^{u}$	Start-up cost of plant i at node n [€]
$d_{j,t,n}$	Electricity demand at day j hour t node n [MW]
$mdt_{i,n}$	Minimum downtime of plant i at node n [h]
$mut_{i,n}$	Minimum uptime of plant i at node n [h]
$Pmax_{i,n}$	Maximum output of plant i at node n [MW]
$Pmin_{i,n}$	Minimum output of plant i at node n [MW]
$PTDF_{l,n}$	Power transmission distribution factor of line l at node n [-]
$ramp_{i,n}$	Maximum ramping up/down rate of plant i at node n [-]
$resil$	Resilience factor of the day-ahead market price of electricity [-]
$regulation_{j,t,q}$	Total volume required for the upward or downward regulation energy [MWh]
RC_n	Generic term referring to the remaining charge capacity of storage unit at the end of last auction
RD_n	Generic term referring to the remaining discharge capacity of storage unit at the end of last auction
RE_n	Generic term referring to the remaining energy storage capacity of storage unit at the end of last auction
SC_n	Maximum charge capacity of storage unit at node n [MW]
SD_n	Maximum discharge capacity of storage unit at node n [MW]
SE_n	Maximum energy storage capacity of storage unit at node n [MWh]
μ_n	Storage conversion efficiency of storage unit at node n[-]
Variables	
$CF_{i,j,t,n}$	Fuel cost function of plant i at node n at day j hour t [€/h]
$CF_{i,j,t,n}^{plus}$	Fuel cost function of plant i at node n at day j hour t after increase of generation [€/h]
$CF_{i,j,t,n}^{minus}$	Fuel cost function of plant i at node n at day j hour t after decrease of generation [€/h]

$CU_{i,j,t,n}$	Start-up cost of plant i at node n at day j hour t [€]
$CU_{i,j,t,n}^{plus}$	Start-up cost of plant i at node n at day j hour t after increase of generation [€]
$CU_{i,j,t,n}^{minus}$	Start-up cost of plant i at node n at day j hour t after decrease of generation [€]
$Charge_{j,t,n}$	Amount of energy injected into storage unit of node n at the end of hour t of day j [MW]
$Discharge_{j,t,n}$	Amount of energy withdrawn from storage unit of node n at the end of hour t of day j [MW]
$E_{j,t,n}$	The energy level in reservoir after the charge or discharge action of storage unit at node n, at the end of hour t of day j
$flow_{j,t,l}$	Active power flow on line l at hour t of day j [MW]
$g_{i,j,t,n}$	Electricity generation of plant i at node n at day j, hour t [MW]
$g_{i,j,t,n}^{a}$	Electricity generation between Pmin and Pint of plant i at node n, hour t of day j [MW]
$g_{i,j,t,n}^{b}$	Electricity generation between Pint and Pmax of plant i at node n, hour t of day j [MW]
$g_{i,j,t,n}^{plus}$	Increase of generation of plant i at node n at day j, hour t [MW]
$g_{i,j,t,n}^{minus}$	decrease of generation of plant i at node n at day j, hour t [MW]
$inj_{j,t,n}$	Active power injection in the network at node n, hour t of day j [MW]
$u_{i,j,t}^{up}$	Binary indicating whether plant i at node n just starts up at hour t of day j: 1 if starting up, 0 if not
$u_{i,j,t}^{down}$	Binary indicating whether plant i at node n just shuts down at hour t of day j: 1 if starting up, 0 if not
$v1_{i,j,t,n}$	Binary indicating the on-off state of plant i at node n after an increase of production at hour t of day j
$v2_{i,j,t,n}$	Binary indicating the on-off state of plant i at node n after a decrease of production at hour t of day j
$v3_{i,j,t,n}$	Binary indicating the on-off state of plant i at node n after final adjustment of production at hour t of day j
$y_{j,t}$	Binary indicating whether the net action after the use of storage in one auction is charging the storage unit or not: 1 if yes, 0 if not.
$z_{i,j,t,n}$	Binary indicating whether plant i at node n is committed or not at hour t of day j: 1 if committed, 0 if not

Equation Section (Next)

Module A: week-ahead auction

In the week-ahead auction, a supplier may use storage to lower down his supply cost by economizing the part-load cost and start-up cost of power plants which should have occurred in order to follow the varying load without storage. At this stage, the network dimension does not need to be taken into account by the actor.

The use of storage will be optimized over the whole week. Index t' refers to the set of 168 hours during a week. The actor needs to ensure that the energy level at the end of the week is equal to the initial energy level in the reservoir.

A1. Objective function

The objective function of the supplier is a single cost function to be minimized:

$$minimize \quad obj = \sum_{i,t'} \left(CF_{i,t'} + CU_{i,t'} \right) \qquad t' \in (1,2,...,168) \tag{1.1}$$

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

$CF_{i,t'}$: fuel cost function of plant i at node n, hour t' of the week [€/h]

$CU_{i,t'}$: start-up cost function of plant i at node n, hour t' of the week [€/h]

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

$$d_{t'} = \sum_i g_{i,t'} + charge_{t'}^w - discharge_{t'}^w \qquad t' \in (1,2,...,168) \tag{1.2}$$

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

$charge_{t'}^w$: amount of energy charged into the storage at hour t' of the week in the week-ahead auction [MW]

$discharge_{t'}^w$: amount of energy discharged from the storage at hour t' of the week in the week-ahead auction [MW]

$$g_{i,t'} = Pmin_i \cdot z_{i,t'} + g_{i,t'}^a + g_{i,t'}^b \tag{1.3}$$

$$g_{i,t'}^{a} \leq \left(Pint_i \ - Pmin_i\right) \cdot z_{i,t'} \tag{1.4}$$

$$g_{i,t'}^{b} \leq (Pmax_i - Pint_i) \cdot z_{i,t'} \tag{1.5}$$

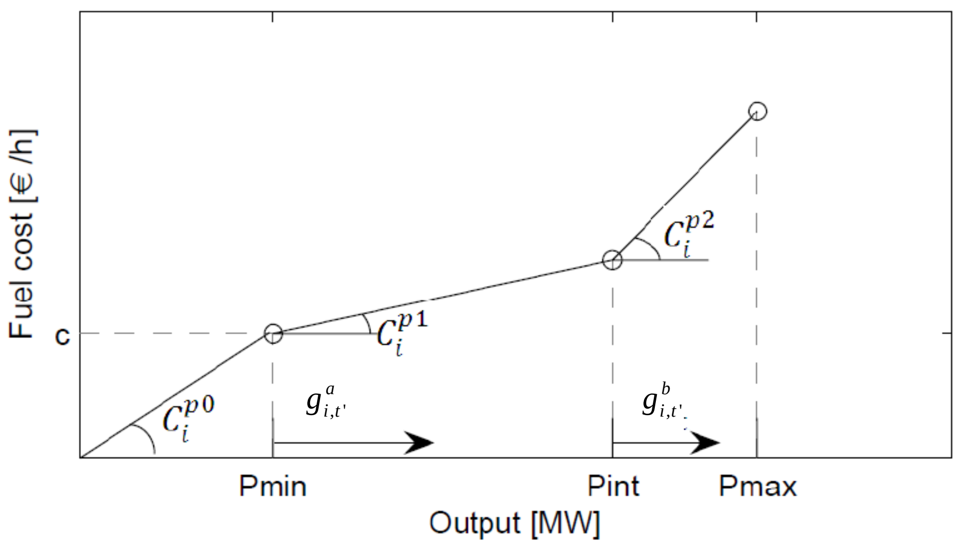
with $g_{i,t'}^{a}$: electricity generation between Pmin and Pint of plant i at hour t' of the week [MW]
$g_{i,t'}^{b}$: electricity generation between Pint and Pmax of plant i at hour t' of the week [MW]
$Pint_i$: intermediate output of plant i [MW]
$Pmax_i$: maximum output of plant i [MW]
$Pmin_i$: minimum output of plant i [MW]
$z_{i,t'}$: binary indicating whether plant i is committed or not at hour t' of the week: 1 if committed, 0 if not

The fuel cost function is written as:

$$CF_{i,t'} = C_i^{p0} \cdot Pmin_i \cdot z_{i,t'} + C_i^{p1} \cdot g_{i,t'}^{a} + C_i^{p2} \cdot g_{i,t'}^{b} \tag{1.6}$$

with C_i^{p0}: average fuel cost at minimum output of plant i [€/ MWh]
C_i^{p1}: marginal fuel cost at first part of maximum output of plant i [€/ MWh]
C_i^{p2}: marginal fuel cost at second part of maximum output of plant i [€/ MWh]

Figure 2. Stepwise cost function of power plant



The start-up cost is :

$$CU_{i,t'} \geq C_i^u \cdot (z_{i,t'} - z_{i,t'-1})$$
$$CU_{i,t'} \geq 0 \qquad (1.7)$$

with C_i^u : start-up cost at minimum output of plant i [€]

A2. Minimum up- and downtimes constraints

For the inclusion of minimum up- and downtimes, the following constraints are constructed:

$$\forall i \in I, \forall k \in [1, 2, ..., mut_i - 1]$$
$$[z_{i,t'} - z_{i,t'-1}] + [z_{i,t'+k-1} - z_{i,t'+k}] \leq 1 \qquad t' \in (1,2,...,168) \qquad (1.8)$$

$$\forall i \in I, \forall k \in [1, 2, ..., mdt_i - 1]$$
$$[z_{i,t'-1} - z_{i,t'}] + [z_{i,t'+k} - z_{i,t'+k-1}] \leq 1 \qquad t' \in (1,2,...,168) \qquad (1.9)$$

with mdt_i: minimum downtime of plant i [h]
mut_i: minimum uptime of plant i [h]

The first terms between brackets in (1.8) and (1.9) reflect a start-up or a shut-down respectively, the second guarantees that the plant remains on- or off-line during the required number of hours.

A3. Ramp rate constraints

$$g_{i,t'} - g_{i,t'-1} \leq Pmax_i \cdot ramp_i + Pmax_i \cdot u_{i,t'}^{up} \qquad (1.10)$$

$$u_{i,t'}^{up} \geq z_{i,t'} - z_{i,t'-1} \qquad (1.11)$$

$$u_{i,t'}^{up} + z_{i,t'-1} \leq 1 \qquad (1.12)$$

$$g_{i,t'-1} - g_{i,t'} \leq Pmax_i \cdot ramp_i + Pmax_i \cdot u_{i,t'}^{down} \qquad (1.13)$$

$$u_{i,t'}^{down} \geq z_{i,t'-1} - z_{i,t'} \qquad (1.14)$$

$$u_{i,t'}^{down} + z_{i,t'-1} \leq 1 \qquad (1.15)$$

with ramp$_i$: maximum ramping rate of plant i [-]

$u_{i,t'}^{up}$: Binary indicating whether plant i starts up or not at hour t of day j: 1 if just starts up, 0 if not

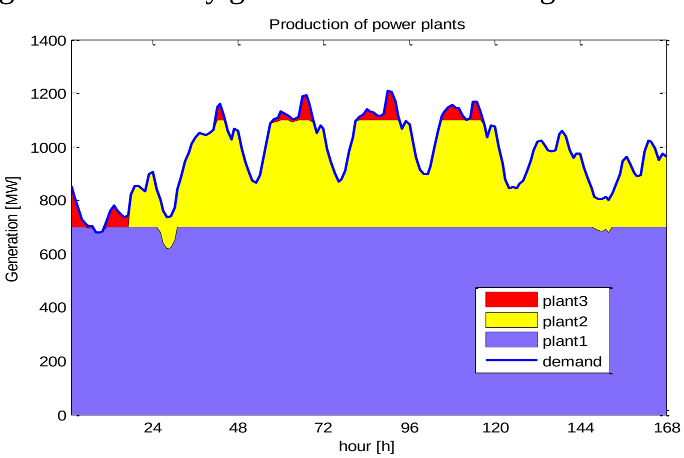
$u_{i,t'}^{down}$: Binary indicating whether plant i shuts down or not at hour t of day j: 1 if just shuts down, 0 if not

(1.10) - (1.12) specify the ramp up constraint for the power plant. If the plant just starts up at hour t of day j, the last term of (1.10) allows the plant to reach immediately at its maximum capacity. In other words, it relaxes the ramp limit for the start-up hour. If the plant is already on line, the last term equals to zero, which enforces the production increase per time step to be less than $Pmax_i \cdot ramp_i$.

(1.13) - (1.15) specify the ramp down constraint for the power plant. Similarly, if the plant just shuts down at hour t of day j, the last term of (1.13) allows the plant to shut down from maximum capacity. If the plant is already on line, the last term equals to zero, which enforces the production decrease per time step to be less than $Pmax_i \cdot ramp_i$.

Figure 4 illustrates the production scheduling of three power plants to meet the demand without use of storage during one week. Plant 1, 2 and 3 represent a base-load, intermediate-load and peak-load generation technology. More information about input parameters can be found in Appendices.

Figure4. Electricity generation without storage



A4. Constraints applied to the storage unit

Supposing that there is no auction prior to the week-ahead auction, the exploration of the storage unit should obey the following constraints:

$$charge_{t'}^{w} \leq SC \tag{1.16}$$

$$discharge_{t'}^{w} \leq SD \tag{1.17}$$

$$E_{t'}^{w} = E_{t'-1}^{w} + charge_{t'}^{w} \cdot \mu - discharge_{t'}^{w} \cdot \frac{1}{\mu} \tag{1.18}$$

$$0 \leq E_{t'}^{w} \leq SE \tag{1.19}$$

$$E_{initial} = \frac{SD}{SD+SE} \cdot SE \tag{1.20}$$

$$E_{t_0'}^{w} = E_{tlast'}^{w} = E_{initial} \tag{1.21}$$

with $E_{t'}^{w}$: energy level in reservoir after the charge or discharge action of storage unit at the end of hour t' of the week in the week-ahead auction [MWh]
$E_{initial}$: initial energy level in reservoir [MWh]
jfirst: first day of the week
jlast: last day of the week
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]
t_0: beginning of the first hour of the week
tlast: last hour of the day
μ: charge or discharge efficiency of the storage unit [-]

(1.16)-(1.17) refers to the maximum charge, discharge, energy capacity limit;

(1.18) establishes the inter-temporal changes of the energy level in storage. There is an efficiency loss during the charge phase and discharge phase. $charge_{t'}^{w}$ is the amount electric energy that the storage unit takes from the network in order to charge the storage unit. is the amount of energy stored in the reservoir after converting the electric energy to another storable form of energy. $discharge_{t'}^{w}$ is the amount of electric energy that the storage unit feed into the network. The energy needed to re-produce this amount of electric energy is $discharge_{t'}^{w} \cdot \frac{1}{\mu}$.

(1.19) set the boundaries on the energy level after the charge/discharge action.

(1.20) defines the initial energy level in storage before the auction. The initial energy is set to the level that allows equal duration of charge and discharge at maximum capacity.

(1.21) 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 equal to the initial energy level in storage.

We can then obtain the desired utilization profile of storage which is a set of $[charge_{t'}^{w}, discharge_{t'}^{w}]$ during the underlying week. The value that the bidder attaches to this use of storage can be considered as the difference between the total cost of meeting the demand without storage and that with storage.

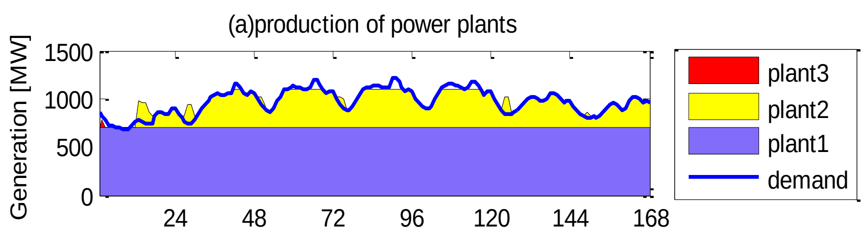
Figure 5 illustrate that by using the storage unit, the supplier can minimize the use of expensive peak-load unit and avoid some part-load losses. In the case study, the storage unit is supposed to have the characteristics indicated by Table 2.

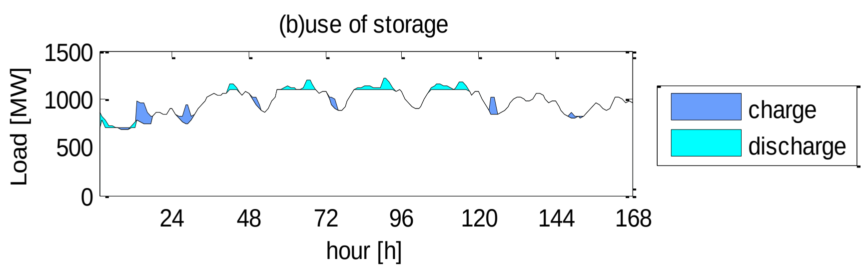
Table 2. Storage unit characteristics

storage unit	SC	SD	SE	μ_{charge}	$\mu_{discharge}$
unit	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 [-]

Figure5. Electricity generation without storage





Equation Section (Next)

Module B: day-ahead auction

In the day-ahead auction, a trader can use storage to do arbitrage on the day-ahead spot market. The spot market price of electricity is often viewed as exogenous variable in current study. However, a player's bid may have an effect on the final price of electricity which is the result of intersection of offer and demand curve. In our analysis, we will incorporate the market resilience factor, which indicates the price sensitivity to an increase in offer or demand, into the optimization algorithm of the trader. It means that 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 his optimal arbitrage strategy.

The available storage capacities for the day-ahead auction are given by the equation (2.1) - (2.3). The index t' referring to 168 hours of the week is now represented jointly by index j, referring to the day of the week, and index t, referring to the hour of the day. The value of $charge_{t'}^{w}$ and $discharge_{t'}^{w}$ will be fit into the corresponding $charge_{j,t}^{w}$ $charge_{j,t}^{w}$

$$\begin{aligned}
&charge_{j,t}^{w} = charge_{t'}^{w} \\
&discharge_{j,t}^{w} = discharge_{t'}^{w} \\
&E_{j,t}^{w} = E_{t'}^{w} \\
&(j-1)\cdot 7 + t = t' \qquad j \in (1,2,...,7) \quad t \in (1,2,...,24)
\end{aligned}$$

The net action on the storage unit in the week-ahead auction is given by (2.1). A positive $netaction_{j,t}^{w}$ implies a charge action, while a negative $netaction_{j,t}^{w}$ implies a discharge action. If there is no week-ahead auction prior to the day-ahead auction, $netaction_{j,t}^{w}$ simply takes the value of zero.

$$netaction_{j,t}^{w} = charge_{j,t}^{w} - discharge_{j,t}^{w} \tag{2.1}$$

$$RC_{j,t}^{d} = SC - netaction_{j,t}^{w} \tag{2.2}$$

$$RD_{j,t}^{d} = SD + netaction_{j,t}^{w} \tag{2.3}$$

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]

If the actor in the week-ahead auction wishes to discharge the storage at a certain time, (2.2) allows that the day-ahead bidder could commercially use the charge capacity higher than the physical capacity of the storage unit, as long as the sum of the discharge and charge action (the net 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, this leaves more room of discharge than the physical discharge capacity to the bidder in the next round of auction. The storage unit, given its unique capacity of being able to operate in two directions, can accommodate perfectly the offsetting actions as described, and generate values for different actors with a limited power rating.

The objective function of the trader is written as:

$$\begin{aligned}&\forall j \in J : maximize \quad profit = \sum_{j,t} [discharge^d_{j,t} \cdot (P_{j,t} + discharge^d_{j,t} \cdot resil) - \\ &charge^d_{j,t} \cdot (P_{j,t} - charge^d_{j,t} \cdot resil)]\end{aligned} \tag{2.4}$$

with $charge^d_{j,t}$: amount of energy charged into the storage at hour t of day j in the day-ahead auction [MW]
$discharge^d_{j,t}$: amount of energy discharged from the storage at hour t of day j in the day-ahead auction [MW]
resil: resilience factor indicating the price change due to an increase in offer or demand on the market [-]. It is by definition negative.
$P_{j,t}$: day-ahead spot price at hour t of day j [€/MWh]

If the storage unit needs to consume external fuel during the discharging phase as the technology of compressed air storage, the objective function should be modified as following:

$$\begin{aligned}&\forall j \in J : profit = \sum_{j,t} [discharge^d_{j,t} \cdot (P_{j,t} + discharge^d_{j,t} \cdot resil - fuelcost) - \\ &charge^d_{j,t} \cdot (P_{j,t} - charge^d_{j,t} \cdot resil)]\end{aligned} \tag{2.5}$$

with fuelcost: fuel cost for re-producing 1MWh of electricity during the discharging phase [€/MWh]

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 following constraints need to be satisfied by the actor in the day-ahead auction:

$$charge^d_{j,t} \le RC^d_{j,t} \tag{2.6}$$

$$discharge^d_{j,t} \le RD^d_{j,t}$$

$$netaction^d_{j,t} = charge^w_{j,t} + charge^d_{j,t} - discharge^w_{j,t} - discharge^d_{j,t} \tag{2.8}$$

$$E_{j,t}^{d} = E_{j,t-1}^{d} + \left(netaction_{j,t}^{d} \cdot y_{j,t}^{d}\right) \cdot \mu - \left[netaction_{j,t}^{d} \cdot (1 - y_{j,t}^{d})\right] \cdot \frac{1}{\mu} \tag{2.9}$$

$$0 \le E_{j,t}^{d} \le SE \tag{2.10}$$

$$E_{j,tlast}^{d} = E_{j,tlast}^{w} \tag{2.11}$$

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

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

$y_{j,t}^{d}$: 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.

(2.6)-(2.7) states that the charge (or discharge) action allowed in day-ahead auction should be less than the remaining charge (or discharge) capacity after the week-ahead auction .

(2.8) calculates the net action after the day-ahead use of storage. The energy level in the reservoir is related only to the final use of storage at the end of the considered auction.

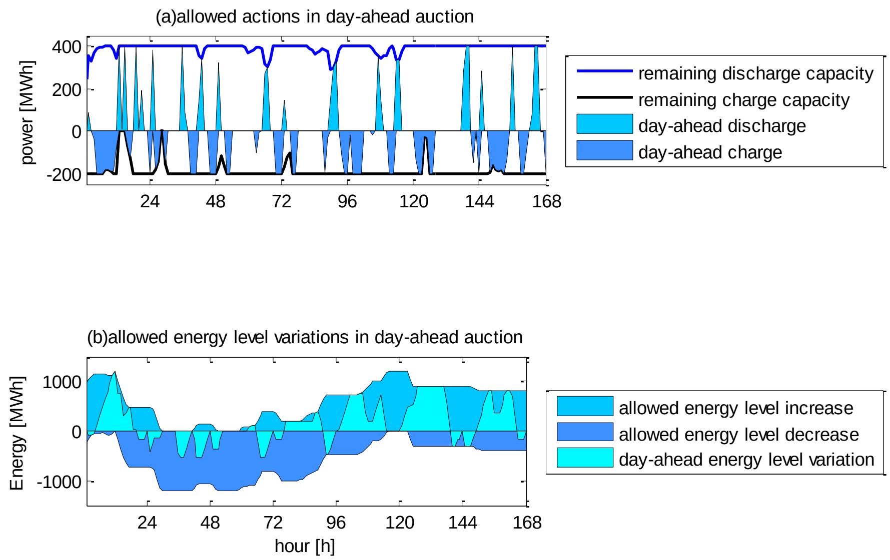
(2.9) gives the energy level in the reservoir after the action taken in the day-ahead auction. The avoided efficiency loss because of the offsetting actions in the two auctions is taken into account by this equation. The energy level should be less than the maximum energy storage capacity and greater than zero, as enforced by (2.10)

(2.11) sets the clearing point. For each day j, the energy level at the last hour should be equal to the energy level established in the precedent auction, which is the week-ahead auction in this case. In this way, the energy level at the beginning of the next day remains unaffected by the day-ahead auction. The day-ahead bidder uses the storage as a pure flexibility asset, with an energy balance equal to zero at the end of the optimization period.

Figure 6 demonstrates how the trader optimizes the use of remaining capacities of the storage unit resulting from the week-ahead auction. Note that Figure 6(b) focus on the energy level variation in the reservoir because of the actions taken in the day-ahead auction. When it is positive, it implies the amount of energy stored in the reservoir is increased after a charge action; when it is negative, it implies the amount of energy stored in the reservoir is decreased after a discharge action.

Figure 7 presents the aggregated charge/discharge action after the week-ahead and the day-ahead auction. 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. Therefore, as illustrated by Figure 8, the energy level is always equal to the energy level established in the week-ahead auction, and the aggregated energy level at the end of the week remains the same to the initial energy level after the week-ahead and day-ahead auction. The storage unit is used as a pure flexibility resource.

Figure6. Allowed actions in day-ahead auction



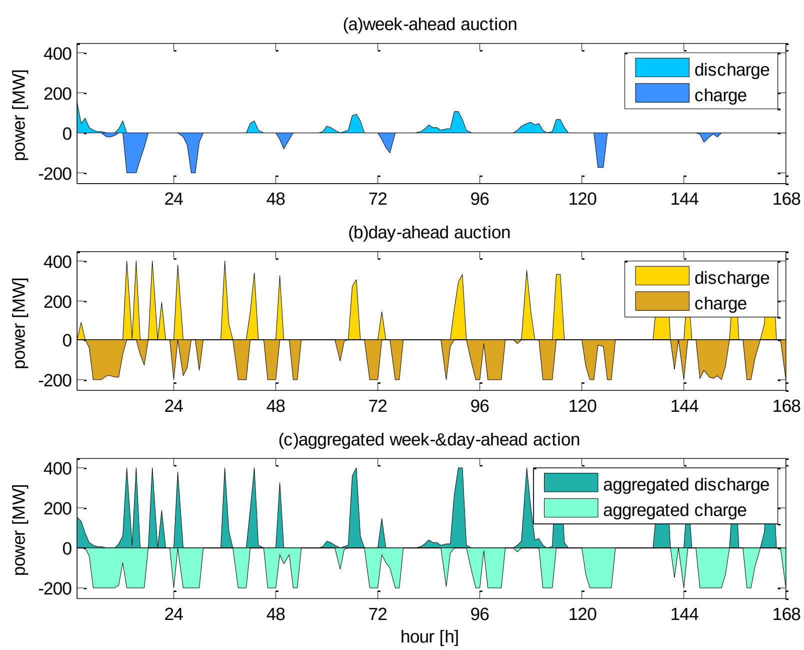
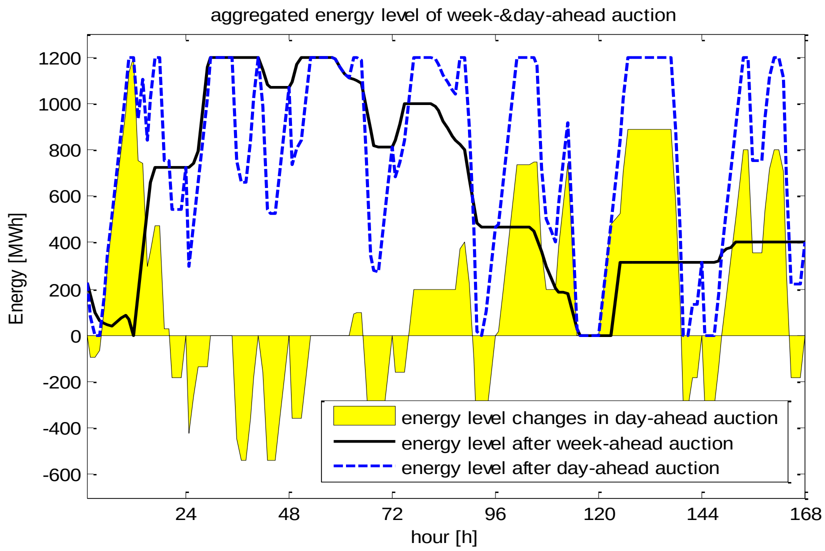


Figure 8. Aggregated energy level after week-ahead and day-ahead auction



After the day-head auction, the aggregated utilization profile of the week-ahead and day-ahead auction will be passed to the next round of auction, in which the right of using the remaining capacities of the storage unit is again auctioned among different actors.

Equation Section (Next)
Module C: 1st intra-day auction

In the first intra-day auction, we simulate the use of storage by the TSO to reduce the congestion cost. The node dimension is taken into account in this case. Again, the available storage capacities for the first intra-day auction are given by the equation (3.1) - (3.3).

Recall that the net action on the storage unit after the day-ahead auction is given by (3.1). A positive $netaction^{d}_{j,t}$ implies a charge action, while a negative $netaction^{d}_{j,t}$ implies a discharge action.

$$netaction^{d}_{j,t} = charge^{w}_{j,t} + charge^{d}_{j,t} - discharge^{w}_{j,t} - discharge^{d}_{j,t} \tag{3.1}$$

$$RC^{x}_{j,t,n} = SC - netaction^{d}_{j,t} \tag{3.2}$$

$$RD^{x}_{j,t,n} = SD + netaction^{d}_{j,t} \tag{3.3}$$

with $RC^{x}_{j,t,n}$: remaining charge capacity for hour t of day j in the first intra-day auction [MW]
$RD^{x}_{j,t,n}$: remaining discharge capacity for hour t of day j in the first intra-day auction [MW]

C1. Calculate the re-dispatch cost without resorting to the storage unit

In the first place, we calculate the re-dispatch cost if the TSO does not resort to the storage unit. Re-dispatch is needed when the commercial contracts signed among market players will lead to overloading of transmission lines. Generators should be re-dispatched in order to meet the network constraints.

C1.1. the objective function

The objective function of the TSO is to minimize the re-dispatch cost as described in equation (3.4). A coefficient for production cost increase and a coefficient for production cost decreased are incorporated into the objective function in order to encourage the least modification of the established production program.

$$\Delta C_{nos} = \sum_{i,j,t,n} [(\Delta CF^{plus}_{i,j,t,n} + \Delta CU^{plus}_{i,j,t,n}) \cdot coef^{up} + (\Delta CF^{minus}_{i,j,t,n} + \Delta CU^{minus}_{i,j,t,n}) \cdot coef^{down}] \tag{3.4}$$

with ΔC_{nos} : re-dispatch cost without resorting to the storage unit [€]

$coef^{up}$: coefficient applied to the production cost increase, which is greater than 1 [-]

$coef^{down}$: coefficient applied to the production cost increase, which is between 0 and 1 [-]

$\Delta CF_{i,j,t,n}^{plus}$: fuel cost increase of plant i at node t, hour t of day j [€/h]

$\Delta CF_{i,j,t,n}^{minus}$: fuel cost decrease of plant i at node t, hour t of day j [€/h]

$\Delta CU_{i,j,t,n}^{plus}$: start-up cost increase of plant i at node t, hour t of day j [€/h]

$\Delta CU_{i,j,t,n}^{minus}$: start-up cost decrease of plant i at node t, hour t of day j [€/h]

C1.2. the power balance

The demand and supply equality is enforced by (3.5). At the right side of the equation, the energy charged into or discharged from the storage unit remains the same as the initial day-ahead plan of storage operation. By contrast, the generation level $g_{i,j,t,n}^{new}$ may differ from the initially programmed generation level $g_{i,j,t,n}$.

$$\forall j \in J, \forall t \in T : \sum_{n} d_{j,t,n} + netation_{j,t,n}^{d} = \sum_{i,n} g_{i,j,t,n}^{new} \tag{3.5}$$

with $g_{i,j,t}^{new}$: electricity generation of plant i at node n, hour t of day j after re-dispatch[MW]

C1.3. the re-dispatch cost function

In order to eliminate the network bottleneck, the TSO should make the decision among increase or decrease the output of a power plant. Such decisions would be based on the economic consequence of the considered actions. The following equations expose how the impact of the adjustment action on the production cost is estimated.

(3.6) - (3.10) shows the calculation of increased fuel cost if the TSO wishes to increase the output of plant i at node n, hour t of day j. The same stepwise cost function is applied to the production level after the adjustment action in order to account for the part-load efficiencies.

$$\Delta CF_{i,j,t,n}^{plus} = CF_{i,j,t,n}^{plus} - CF_{i,j,t,n} \tag{3.6}$$

$$CF_{i,j,t,n}^{plus} = C_{i,n}^{p0} \cdot Pmin_{i,n} \cdot v_{i,j,t,n}^{1} + C_{i,n}^{p1} \cdot g_{i,j,t,n}^{aplus} + C_{i,n}^{p2} \cdot g_{i,j,t,n}^{bplus} \tag{3.7}$$

$$g_{i,j,t,n} + g_{i,j,t,n}^{plus} = Pmin_{i,n} \cdot v_{i,j,t,n}^{1} + g_{i,j,t,n}^{aplus} + g_{i,j,t,n}^{bplus} \tag{3.8}$$

$$g_{i,j,t,n}^{aplus} \leq (Pint_{i,j,t,n} - Pmin_{i,j,t,n}) \cdot v_{i,j,t,n}^{1} \tag{3.9}$$

$$g_{i,j,t,n}^{bplus} \leq (Pmax_{i,j,t,n} - Pint_{i,j,t,n}) \cdot v_{i,j,t,n}^{1} \tag{3.10}$$

with $CF_{i,j,t,n}^{plus}$: fuel cost if the output of plant i at node n is increased at hour t of day j [€/h]

$g_{i,j,t,n}^{plus}$: electricity generation increase of plant i at node n, hour t of day j [MW]

$g_{i,j,t,n}^{aplus}$: electricity generation between Pmin and Pint of plant i at hour t of day j if there is an increase of output [MW]

$g_{i,j,t,n}^{bplus}$: electricity generation between Pint and Pmax of plant i at hour t of day j if there is an increase of output [MW]

$v_{i,j,t,n}^{1}$: binary indicating the on-off state of plant i at node n if there is an increase of production at hour t of day j: 1 if committed, 0 if not

(3.11) - (3.15) shows the calculation of saved fuel cost if the TSO wishes to decrease the output of plant i at node n, hour t of day j. $\Delta CF_{i,j,t,n}^{minus}$ is negative.

$$\Delta CF_{i,j,t,n}^{minus} = CF_{i,j,t,n}^{minus} - CF_{i,j,t,n} \tag{3.11}$$

$$CF_{i,j,t,n}^{minus} = C_{i,n}^{p0} \cdot Pmin_{i,n} \cdot v_{i,j,t,n}^{2} + C_{i,n}^{p1} \cdot g_{i,j,t,n}^{aminus} + C_{i,n}^{p2} \cdot g_{i,j,t,n}^{bminus} \tag{3.12}$$

$$g_{i,j,t,n} + g_{i,j,t,n}^{minus} = Pmin_{i,n} \cdot v_{i,j,t,n}^{2} + g_{i,j,t,n}^{aminus} + g_{i,j,t,n}^{bminus} \tag{3.13}$$

$$g_{i,j,t,n}^{aminus} \leq (Pint_{i,j,t,n} - Pmin_{i,j,t,n}) \cdot v_{i,j,t,n}^{2} \tag{3.14}$$

$$g_{i,j,t,n}^{bminus} \leq (Pmax_{i,j,t,n} - Pint_{i,j,t,n}) \cdot v_{i,j,t,n}^{2} \tag{3.15}$$

with $CF_{i,j,t,n}^{minus}$: fuel cost if the output of plant i at node n is decreased at hour t of day j [€/h]

$g_{i,j,t,n}^{minus}$: electricity generation increase of plant i at node n, hour t of day j [MW]

: electricity generation between Pmin and Pint of plant i at hour t of day j if there is a decrease of output [MW]

$g_{i,j,t,n}^{bminus}$: electricity generation between Pint and Pmax of plant i at hour t of day j if there is a decrease of output [MW]

$v_{i,j,t,n}^{2}$: binary indicating the on-off state of plant i at node n if there is a decrease of production at hour t of day j: 1 if committed, 0 if not

The TSO will arbitrage between increase or decrease the output of generator at each time step. The optimization algorithm will give the optimal action that minimizes the adjustment cost over the whole optimization period. The final generation of the power plant after adjustment is written as:

$$g_{i,j,t,n}^{new} = g_{i,j,t,n} + g_{i,j,t,n}^{plus} - g_{i,j,t,n}^{minus} \tag{3.16}$$

(3.17) - (3.18) shows the calculation of increased start-up cost if the TSO wishes to increase the output of plant i at node n, hour t of day j:

$$CU_{i,j,t,n}^{new} \geq C_{i,j,t,n}^{u} \cdot (v_{i,j,t,n}^{3} - v_{i,j,t-1,n}^{3}) \tag{3.17}$$

$$\Delta CU_{i,j,t,n}^{plus} = \left(CU_{i,j,t,n}^{new} - CU_{i,j,t,n}\right) \cdot m \tag{3.18}$$

$$\Delta CU_{i,j,t,n}^{minus} = \left(CU_{i,j,t,n}^{new} - CU_{i,j,t,n}\right) \cdot \left(1 - m\right) \tag{3.19}$$

$$\begin{aligned} m &= 1 \quad if\, CU_{i,j,t,n}^{new} - CU_{i,j,t,n} \geq 0 \\ m &= 0 \quad if\, CU_{i,j,t,n}^{new} - CU_{i,j,t,n} < 0 \end{aligned} \tag{3.20}$$

with $CU_{i,j,t,n}^{minus}$: start-up cost decrease of plant i at node n following the adjustment action at hour t of day j [€/h]

$CU_{i,j,t,n}^{new}$: final start-up cost after the adjustment action on plant i at node n at hour t of day j [€/h].

$CU_{i,j,t,n}^{plus}$: start-up cost increase of plant i at node n following the adjustment action at hour t of day j [€/h].

m: binary indicating whether there is a start-up cost increase following the final adjustment action. 1 if yes, 0 if not.

(3.21) resumes the relationship between the binaries:

$$v_{i,j,t,n}^{1} + v_{i,j,t,n}^{2} = z_{i,j,t,n} + v_{i,j,t,n}^{3} \tag{3.21}$$

$v_{i,j,t,n}^{1}$ indicates the on-off state of the power plant if there is an increase of production at hour t of day j. It takes value of 0 when the initial state $z_{i,t,j,n} = 0$, and the increased output is 0; it takes value of 1 when increased output is positive.

$v_{i,j,t,n}^{2}$ indicates the on-off state of the power plant if there is a decrease of production at hour t of day j. It takes value of 1 when the initial state $z_{i,t,j,n} = 1$, and the plant is still on line after decreasing the output; it takes the value of 0 when the initial state $z_{i,t,j,n} = 0$ or when the plant is off line after decreasing the output.

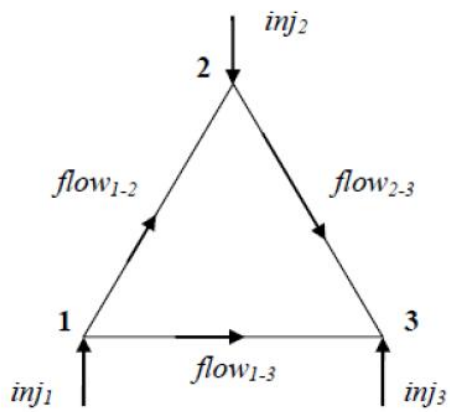
$v^1_{i,j,t,n}$ should always be larger than $v^2_{i,j,t,n}$, because it is impossible for the power plant to be off-line after increasing its output ($v^1_{i,j,t,n}$=0) while it is on-line after decreasing its output ($v^2_{i,j,t,n}$=1).

Constraint (3.21) will enforce that, if the on-off state of the power plant is not changed after re-dispatch, $v^1_{i,j,t,n} = v^2_{i,j,t,n} = z_{i,t,j,n} = v^3_{i,j,t,n}$; if the on-off state of the power plant is changed after re-dispatch, $v^1_{i,j,t,n}$=max[$z_{i,t,j,n}$, $v^3_{i,j,t,n}$] and $v^2_{i,j,t,n}$=min[$z_{i,t,j,n}$, $v^3_{i,j,t,n}$].

C1.4. power flow and network constraint

The network constraints are incorporated through the implementation of a DC load flow. In the present work, the network in study is supposed to be triangular, as illustrated by figure 2.

Figure 2. Triangular network example



Matrix (3.22) represents relationship between flows over lines and nodal injections. $PTDF_{k,n\text{-}m}$ is flow on line n-m caused by a unit of injection in node k and withdrawal of this same injection at the reference (swing) node. In (3.22), node 1 is the reference node.

$$\begin{bmatrix} PTDF_{2,12} & PTDF_{3,12} \\ PTDF_{2,13} & PTDF_{3,13} \\ PTDF_{2,23} & PTDF_{3,23} \end{bmatrix} \cdot \begin{bmatrix} inj_2 \\ inj_3 \end{bmatrix} = \begin{bmatrix} flow_{12} \\ flow_{13} \\ flow_{23} \end{bmatrix} \tag{3.22}$$

In general form, this relationship between injection and flows can be written as:

$$\forall j \in J, \forall t \in T, \forall l \in L : \sum_n PTDF_{l,n} \cdot inj_{j,t,n} = flow_{j,t,l} \tag{3.23}$$

with $PTDF_{l,n}$: ower transmission distribution factor of line l and node n [-]

$inj_{j,t,n}$: active power injection in the network at node n, hour t of day j [MW]

$flow_{j,t,l}$: active power flow on line l at hour t of day j [MW]

The injection of active power in the network is defined as the difference of what is generated and consumed at the node n. (3.24) represents the power flow after the re-dispatch process without resorting to the storage unit.

$$\forall j \in J, \forall t \in T : inj^{nos}_{j,t,n} = \sum_i g^{new}_{i,j,t,n} - d_{j,t,n} - netaction^d_{j,t,n} \qquad (3.24)$$

with $inj^{nos}_{j,t,n}$: active power injection in the network at node n, hour t of day j after re-dispatch without storage [MW]

C2. Calculate the re-dispatch cost using the remaining capacities of the storage unit

In the second place, we calculate the re-dispatch cost if it is possible for the TSO to explore the remaining capacities of the storage unit. The objective function is to minimize the re-dispatch cost with least modification on the initial production plan, which is the same as in the scenario without resorting to the storage unit.

$$\Delta C_{sto} = \sum_{i,j,t,n} [(\Delta CF^{plus}_{i,j,t,n} + \Delta CU^{plus}_{i,j,t,n}) \cdot coef^{up} + (\Delta CF^{minus}_{i,j,t,n} + \Delta CU^{minus}_{i,j,t,n}) \cdot coef^{down}] \qquad (3.25)$$

However, by using the remaining capacities of the storage unit, the power balance is replaced by (3.26), where $netaction^x_{j,t,n}$ can differ from the net action after the day-ahead auction of use of storage.

$$\forall j \in J, \forall t \in T : \sum_n d_{j,t,n} + netaction^x_{j,t,n} = \sum_{i,n} g^{new}_{i,j,t,n} \qquad (3.26)$$

$$\begin{aligned} netaction^x_{j,t,n} = {} & charge^w_{j,t,n} + charge^d_{j,t,n} + charge^x_{j,t,n} - \\ & \left(discharge^w_{j,t,n} + discharge^d_{j,t,n} + discharge^x_{j,t,n} \right) \end{aligned} \qquad (3.27)$$

with $charge^x_{j,t,n}$: amount of energy charged into the storage at node n, hour t of day j in the 1st intra-day auction [MW]

$discharge^x_{j,t,n}$: amount of energy discharged from the storage at node n, hour t of day j in the 1st intra-day auction [MW]

$netaction^x_{j,t,n}$: net action on the storage unit node n, hour t of day j after the 1st intra-day use of storage [MW]

(3.27) calculates the net action after the day-ahead use of storage. The energy level in the reservoir is related only to the final use of storage at the end of the considered auction.

The desired utilization of the storage unit by the TSO to reduce the re-dispatch cost should nevertheless satisfy the following constraints:

$$charge^{x}_{j,t,n} \leq RC^{x}_{j,t,n} \tag{3.28}$$

$$discharge^{x}_{j,t,n} \leq RD^{x}_{j,t,n} \tag{3.29}$$

$$E^{x}_{j,t,n} = E^{x}_{j,t-1,n} + \left(netaction^{x}_{j,t,n} \cdot y^{x}_{j,t,n}\right) \cdot \mu - \left[netaction^{x}_{j,t,n} \cdot (1 - y^{x}_{j,t,n})\right] \cdot \frac{1}{\mu} \tag{3.30}$$

$$0 \leq E^{x}_{j,t,n} \leq SE \tag{3.31}$$

$$E^{x}_{j,tlast,n} = E^{d}_{j,tlast,n} \tag{3.32}$$

with $E^{x}_{j,t,n}$: energy level in the reservoir after the charge or discharge action at the end of hour t of day j in the 1st intra-day auction [MWh]

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

(3.28)-(3.29) states that the charge (or discharge) action allowed in the first intra-day auction should be less than the remaining charge (or discharge) capacity after the precedent auction;

(3.30) gives the energy level in the reservoir after the action taken in the 1st intra-day auction. The avoided efficiency loss because of the offsetting actions in the two auctions is taken into account by this equation. The energy level should be less than the maximum energy storage capacity and greater than zero, as enforced by (3.31);

(3.32) sets the clearing point. For each day j, the energy level at the last hour should be equal to the energy level established in the precedent auction. The bidder in this auction always uses the storage as a pure flexibility asset, with an energy balance equal to zero at the end of the optimization period.

The power flow after the re-dispatch process with the help of the storage unit is written as:

$$\forall j \in J, \forall t \in T : inj^{sto}_{j,t,n} = \sum_{i} g^{new}_{i,j,t,n} - d_{j,t,n} - netaction^{x}_{j,t,n} \tag{3.33}$$

with $inj^{sto}_{j,t,n}$: active power injection in the network at node n, hour t of day j after re-dispatch with storage [MW]

The contribution of storage in reducing the re-dispatch cost is given by:

$$value_{redispatch} = \Delta C_{nos} - \Delta C_{sto} \tag{3.34}$$

Equation Section (Next)

Module D: 2nd intra-day auction – Reduction of wind deviation cost with remaining storage capacities

In the second intra-day auction, we simulate the use of storage by the wind producer to reduce the deviation cost due to inaccurate forecast of wind output. The node dimension is not going to be taken into account in this case, as it is not the task of market participant to deal with the eventual network congestion.

Recall that the net action on the storage unit after the 1st intra-day auction is given by (4.1). A positive $netaction_{j,t}^{x}$ implies a charge action, while a negative $netaction_{j,t}^{x}$ implies a discharge action. The available storage capacities for the second intra-day auction are given by the equation (4.2) - (4.3).

$$netaction_{j,t}^{x} = \left(charge_{j,t}^{w} + charge_{j,t}^{d} + charge_{j,t}^{x}\right) - \left(discharge_{j,t}^{w} + discharge_{j,t}^{d} + discharge_{j,t}^{x}\right) \tag{4.1}$$

$$RC_{j,t}^{y} = SC - netaction_{j,t}^{x} \tag{4.2}$$

$$RD_{j,t}^{y} = SD + netaction_{j,t}^{x} \tag{4.3}$$

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

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

As wind is an intermittent energy resource, forecasting wind power output inevitably leads to forecast errors. These errors would entail additional cost for the system to compensate the wind deviation in short notice. The financial responsibility for the wind deviation differs in different countries and in different wind support scheme. For example, in Germany the wind producers carry no imbalance risk, while in Spain the wind producer should pay imbalance charges for schedule deviations. In this report, we study the Spanish case where the wind producer is exposed to imbalance risk due to inaccurate forecast. In Spain, a wind producer can opt between the Feed-in-Tariff scheme where he receive a regulated tariff for the wind production and pays a fixed rate for schedule deviation, and the market scheme where he sells the wind power on the market and pays the imbalance cost within the market rules. We will study the benefit of storage in reducing the imbalance cost in these two schemes.

D1. Imbalance regulation in the Spanish Feed-in-Tariff scheme

According to the Spanish law, the wind power producer receiving a regulated tariff should communicate their forecasted wind output for the 24 hours next day at least thirty hours advance notice of that day. A deviation cost shall be charged on the difference between the forecast power and the real output delivered is more than 20% higher or lower of the real output. The deviation cost is the product of all the absolute deviations over those thresholds and 10% of the Average Electricity Tariff (AET) published every year, which is 7.8€/ MWh.

D1.1. expected deviation cost without any adjustment by storage

In the first place, we will calculate the expected deviation cost based on the old forecasted that the wind producer has submitted at least thirty hours in advance for the next day. As the real wind output will be known only in real time, the wind producer can only estimate the expected deviation cost with respect to the new forecast.

If the wind producer does not use the storage unit to adjust the old wind power forecast, the amount of deviation that he is supposed to face is given by (4.4)- (4.5).

$$\omega_{j,t}^{old} = \left| wind_{j,t}^{f} - wind_{j,t}^{newf} \right| - 20\% \cdot wind_{j,t}^{newf} \qquad if \;\; \omega_{j,t}^{old} > 0 \tag{4.4}$$

$$otherwise \quad \omega_{j,t}^{old} = 0 \tag{4.5}$$

with $\omega_{j,t}^{old}$: absolute wind forecast deviation larger than 20% of the updated forecast of wind output at hour t of day j [MW]

$wind_{j,t}^{f}$: old forecast of wind output for hour t of day j [MW]

The estimated penalty is given by (4.6):

$$\forall j \in J : penalty_{old} = \sum_{t} \omega_{j,t}^{old} \cdot P_{dev} \tag{4.6}$$

with $penalty_{old}$: estimated deviation cost based on the old forecast of wind [€]

D1.2. Adjustment by storage towards new forecast

When the wind producer has a more accurate forecast of wind output for the 24 hours next day, he would check the deviation between the old forecast and the updated one, and try to limit the absolute deviation within the range of 20% of the newly forecasted wind output. In the case study, a normal distributed error on the wind speed forecast is assumed. The standard deviation for the old forecast is assumed to be 1 m/s. The updated forecast will reduce the error to 0.5 m/s. The wind producer can charge the storage unit when the wind output is underestimated by more than 20% (with respect to the new forecast), and discharge the storage unit when the wind output is overestimated by more than 20% (with respect to the new forecast). This process is described by (4.7)-(4.9).

$$\omega_{j,t}^{adjust} \geq \left| wind_{j,t}^{new} - wind_{j,t}^{newf} \right| - 20\% \cdot wind_{j,t}^{newf} \tag{4.7}$$

$$\omega_{j,t}^{adjust} \geq 0 \tag{4.8}$$

$$wind_{j,t}^{new} = wind_{j,t}^{f} - discharge_{j,t}^{wind} + charge_{j,t}^{wind} \tag{4.9}$$

with $\omega_{j,t}^{adjust}$: absolute wind forecast deviation larger than 20% of the updated forecast of wind output after adjustment by storage [MW]

$charge_{j,t}^{wind}$: wind power charged into the storage unit in order to reduce the positive deviation [MW]

$discharge_{j,t}^{wind}$: wind power charged into the storage unit in order to reduce the negative deviation [MW]

$wind_{j,t}^{newf}$: updated forecast of wind output for hour t of day j [MW]

$wind_{j,t}^{new}$: "adjusted"wind ouput by the storage unit [MW]

The wind producer will try to minimize the penalty corresponding to the deviation between the old forecast power and updated forecast power:

$$\forall j \in J : minimize \quad penalty_{new} = \sum_{t} \omega_{j,t}^{adjust} \cdot P_{dev} \tag{4.10}$$

with $penalty_{new}$: estimated deviation cost based on the newly made forecast of wind output [€]

$$charge_{j,t}^{y} \leq RC_{j,t}^{y} \tag{4.11}$$

$$discharge_{j,t}^{y} \leq RD_{j,t}^{y} \tag{4.12}$$

$$\begin{aligned} netaction_{j,t}^{y} = &\left(charge_{j,t}^{w} + charge_{j,t}^{d} + charge_{j,t}^{x} + charge_{j,t}^{y} \right) - \\ &\left(discharge_{j,t}^{w} + discharge_{j,t}^{d} + discharge_{j,t}^{x} + discharge_{j,t}^{y} \right) \end{aligned} \tag{4.13}$$

$$E_{j,t}^{y} = E_{j,t-1}^{y} + \left(netaction_{j,t}^{y} \cdot y_{j,t}^{y} \right) \cdot \mu - \left[netaction_{j,t}^{y} \cdot (1 - y_{j,t}^{y}) \right] \cdot \frac{1}{\mu} \tag{4.14}$$

$$0 \le E_{j,t}^{y} \le SE \tag{4.15}$$

$$E_{j,tlast}^{y} = E_{j,tlast}^{x} \tag{4.16}$$

with $E_{j,t}^{y}$: energy level in the reservoir after the charge or discharge action at the end of hour t of day j in the second intra-day auction [MWh]

$netaction_{j,t}^{y}$: net action on the storage unit at the end of hour t of day j after the 2^{nd} intra-day use of storage.

$y_{j,t}^{y}$: 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.

(4.11)-(4.12) states that the charge (or discharge) action allowed in the first intra-day auction should be less than the remaining charge (or discharge) capacity after the precedent auction;

(4.13) calculates the net action after the 2^{nd} intra-day use of storage. The energy level in the reservoir is related only to the final use of storage at the end of the considered auction.

(4.14) gives the energy level in the reservoir after the actions taken in the 2^{nd} intra-day auction. The energy level should be less than the maximum energy storage capacity and greater than zero, as enforced by (4.15)

(4.16) sets the clearing point. For each day j, the energy level at the last hour should be equal to the energy level established in the precedent auction. The bidder in this auction always uses the storage as a pure flexibility asset, with an energy balance equal to zero at the end of the optimization period.

The estimated value of storage in order to reduce the imbalance cost in the Feed-in-tariff scheme is written as:

$$value_{imbalance}^{FIT} = penalty_{old} - penalty_{new} \tag{4.17}$$

This value can be considered as the maximum price the wind producer is willing to pay in order to reduce the balancing cost. Note that this value is the “expected” benefit of using storage to reduce the deviation cost. The actual benefit of using storage might be different from the expected one, for that the updated forecast is still not equal to the real wind output, which is revealed in real time. The following sub-section gives the calculation of the value of storage a posterior.

D1.3. Actual avoided deviation cost by storage calculated a posterior

(4.18)-(4.20) calculates the actual penalty that the wind producer has to pay if he does not use the storage unit to adjust the old forecast.

$$\omega_{j,t}^{1} = \left| wind_{j,t}^{f} - wind_{j,t} \right| - 20\% \cdot wind_{j,t} \qquad if \;\; \omega_{j,t}^{1} > 0 \tag{4.18}$$

$$otherwise \quad \omega_{j,t}^{1} = 0 \tag{4.19}$$

$$\forall j \in J : penalty_1 = \sum_t \omega_{j,t}^{1} \cdot P_{dev} \tag{4.20}$$

with $\omega_{j,t}^{1}$: absolute wind forecast deviation larger than 20% of the real output of the wind turbine at hour t of day j [MW]

$wind_{j,t}$: measured output of the wind turbine at hour t of day j [MW]

$penalty_1$: actual deviation cost based on the old forecast of wind output [€]

Although the updated wind forecast should lead to a smaller forecast error compared to the old forecast, it is still not equal to the real wind output. The wind producer should still pay the penalty for the forecast error beyond 20% of the real output.

The penalty the wind producer has to pay after adjustment by storage is given by (4.21)-(4.23):

$$\omega_{j,t}^{2} = \left| wind_{j,t}^{new} - wind_{j,t} \right| - 20\% \cdot wind_{j,t} \qquad if \; \omega_{j,t}^{2} > 0 \tag{4.21}$$

$$otherwise \quad \omega_{j,t}^{2} = 0 \tag{4.22}$$

$$\forall j \in J : penalty_2 = \sum_t \omega_{j,t}^{2} \cdot P_{dev} \tag{4.23}$$

with $penalty_2$: actual deviation cost based on the updated forecast of wind output [€]

The real benefit of storage in reducing the imbalance cost in the Feed-in-tariff scheme is given by:

$$benefit_{imbalance}^{FIT} = penalty_1 - penalty_2 \tag{4.24}$$

The wind producers that opt to sell their electricity into the market will have to fulfill the forecast obligation and pay the deviation costs required within the market rules. So he has to pay 110% of the daily market price for the positive deviation (production is less than what is predicted) and he will receive only 90% of the daily market price for the negative deviation (production is more than what is predicted).

D2.1. Deviation cost without any adjustment by storage

In the first place, we will calculate the estimated total profit if the wind producer does not use storage to adjust the old forecast according to the updated one.

$$profit_{old} = \sum_{j,t} (wind^{f}_{j,t} \cdot P_{j,t} - \varphi^{old}_{j,t} \cdot P_{j,t} - |\, \varphi^{old}_{j,t} \cdot 10\% \cdot P_{j,t} \,|) \tag{4.25}$$

$$\varphi^{old}_{j,t} = wind^{f}_{j,t} - wind^{newf}_{j,t} \tag{4.26}$$

with $\varphi^{old}_{j,t}$: deviation between the old forecast of wind output and the updated one [MW]

$wind^{f}_{j,t}$: old forecast of wind output for hour t of day j [MW]

$P_{j,t}$: spot market price at hour t of day j [€/MWh]

$\varphi^{old}_{j,t}$ is positive when the wind production is less than what is newly predicted. The wind producer should pay 110% of the market price to buy the regulation energy. $\varphi^{old}_{j,t}$ is negative when the wind production is more than what is newly predicted. This power surplus would be reimbursed at only 90% of the market price, which implies an opportunity cost equal to 10% of the market price multiplied by the imbalance volume. Note that the amount of wind energy that the wind producer sells in the day-ahead spot market is always the old forecast wind output which is made to submit bids in the day-ahead spot market.

D2.2. Adjustment by storage towards new forecast

When the wind producer has a more accurate forecast of wind output for the 24 hours next day, he would check the deviation between the old forecast and the updated one, and try to maximize his profit by reducing the imbalance cost.

$$profit_{new} = maximize \sum_{j,t} (wind^{f}_{j,t} \cdot P_{j,t} - \varphi^{adjust}_{j,t} \cdot P_{j,t} - |\, \varphi^{adjust}_{j,t} \cdot 10\% \cdot P_{j,t} \,|) \tag{4.27}$$

$$\varphi^{adjust}_{j,t} = (wind^{f}_{j,t} - wind^{newf}_{j,t}) - discharge^{wind}_{j,t} + charge^{wind}_{j,t} \tag{4.28}$$

with $profit_{new}$: estimated profit after the adjustment by storage according to the newly made forecast of wind output [€]

$\varphi^{adjust}_{j,t}$: wind forecast deviation with respect to the updated forecast of wind output after the adjustment made by storage [MW]

$charge^{wind}_{j,t}$: wind power charged into the storage unit in order to reduce the positive deviation [MW]

$discharge^{wind}_{j,t}$: wind power charged into the storage unit in order to reduce the negative deviation [MW]

$wind_{j,t}^{newf}$: updated forecast of wind output for hour t of day j [MW]

When $wind_{j,t}^{f} - wind_{j,t}^{newf} \geq 0$, wind is overestimated, resulting in a positive imbalance. A penalty equal to 110% of the market price is charge on the imbalance. In order to avoid this penalty, the wind producer may have incentive to discharge storage to fill in the gap. $\varphi_{j,t}^{old}$ is then reduced.

When $wind_{j,t}^{f} - wind_{j,t}^{newf} \leq 0$, wind is underestimated, resulting in a negative imbalance. The revenue received by the wind producer for the negative imbalance is discounted by 10% of the market price. The wind producer would have incentive to charge the storage with the wind power "surplus" in order to discharge this energy later on rather than sell it at 90% of market price.

D2.3. Actual avoided deviation cost by storage calculated a posterior

(4.29)-(4.30) calculates the actual profit of the wind producer if he does not use the storage unit to adjust the old forecast.

$$profit_1 = \sum_{j,t} (wind_{j,t}^{f} \cdot P_{j,t} - \varphi_{j,t}^{1} \cdot P_{j,t} - |\varphi_{j,t}^{1} \cdot 10\% \cdot P_{j,t}|) \tag{4.29}$$

$$\varphi_{j,t}^{1} = wind_{j,t}^{f} - wind_{j,t} \tag{4.30}$$

with $\omega_{j,t}^{1}$: absolute wind forecast deviation larger than 20% of the real output of the wind turbine at hour t of day j [MW]

$profit_1$: actual profit based on the old forecast of wind output [€]

Although the updated wind forecast should lead to a smaller forecast error compared to the old forecast, it is still not equal to the real wind output. The wind producer should still pay the imbalance cost corresponding to deviation after the adjustment by storage.

The actual profit for the wind producer after adjustment by storage is given by (4.31) - (4.32):

$$profit_2 = \sum_{j,t} (wind_{j,t}^{f} \cdot P_{j,t} - \varphi_{j,t}^{2} \cdot P_{j,t} - |\varphi_{j,t}^{2} \cdot 10\% \cdot P_{j,t}|) \tag{4.31}$$

$$\varphi_{j,t}^{2} = \varphi_{j,t}^{1} - discharge_{j,t}^{wind} + charge_{j,t}^{wind} \tag{4.32}$$

with $\varphi^2_{j,t}$: wind forecast deviation with respect to the real wind output after adjustment by storage [MW]

$profit_2$: actual profit after adjustment made by storage [€]

The real benefit of storage in reducing the imbalance cost in the market option scheme is given by:

$$benefit^{market}_{imbalance} = profit_2 - profit_1 \tag{4.33}$$

Equation Section (Next)

Module E: Hour-ahead auction – storage providing regulation energy

In the hour-ahead auction, we study the strategy of a system operator who can continue to explore the remaining storage capacity to provide regulating energy at the real time within one hour. The system operator is interested in using storage during this hour because it could save him the cost of activating the secondary frequency regulation reserves, and eventually save him the capacity cost of a certain amount of reserves if the storage is proved to be able to systematically fulfill such amount of reserve requirement in real time.

The system operator in study tends to maximize the use of available storage capacity 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 activating or not the storage unit to provide the required regulation, but he can by no means control the actual energy charged in or discharged from the storage unit— the system frequency will decide it.

Because of the uncontrollability over the actual energy flow into or out of the storage unit for the regulation service, the actions on the storage within one hour could lead to a change on the energy level at the end of this hour, which might result in the non-respect of the actions established in the precedent auctions in the following hours. Therefore, we need to set some rules in order to ensure that the utilization profiles established in the previous auctions would be respected.

(1) The actor is allowed to explore the storage only for the first 23 hours during the day. The last hour is reserved for the final adjustment action on the storage. During the last hour, the storage owner or the system operator has to bring the net energy level change at the end of 23rd hour back to zero (by buying or selling energy in electricity market) in order not to affect the initial energy level at the beginning of the next day.

(2) The model has to verify at each time step that in the following hours the storage has enough capacity to offset the net energy level change at the end of that time step. If not, the storage will not be activated to provide the regulation energy.

(3) The model has to verify also that at end each time step, the net energy level change will not shift the energy level established in the previous auctions above the maximum energy capacity nor below zero for all the following hours. If it is the case, the storage will not be activated to provide the regulation energy.

We distinguish further two cases of this verification process:

(1) The first one is with full foresight over the regulation direction and volume during the whole period (which is the length of the most extended auction, e.g. one week in our model setting). In this case, a relaxing constraint will be imposed on the

allowed actions on storage within one hour because it always considers the opportunities of the offsetting regulation actions in the following hours.

(2) The second one is with no foresight over the regulation requirement at all, which implies that the system operator has no knowledge of the regulation requirement on the following hours. In this case, a stringent constraint will be imposed without considering any offsetting regulation actions in the following hours.

The results calculated under these two assumptions should set the maximum and minimum boundary of the use of storage by the system operator.

Recall that the net action on the storage unit after the 2nd intra-day auction is given by (5.1). A positive $netaction_{j,t}^{y}$ implies a charge action, while a negative $netaction_{j,t}^{y}$ implies a discharge action. The available storage capacities for the hour-ahead auction are given by the equation (5.2) - (5.3).

$$\begin{aligned} netaction_{j,t}^{y} = &\left(charge_{j,t}^{w} + charge_{j,t}^{d} + charge_{j,t}^{x} + charge_{j,t}^{y}\right) - \\ &\left(discharge_{j,t}^{w} + discharge_{j,t}^{d} + discharge_{j,t}^{x} + discharge_{j,t}^{y}\right) \end{aligned} \tag{5.1}$$

$$RC_{j,t}^{h} = SC - netaction_{j,t}^{y} \tag{5.2}$$

$$RD_{j,t}^{h} = SD + netaction_{j,t}^{y} \tag{5.3}$$

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 objective function of the TSO can be written as:

$$\forall j \in J, \forall t \in (1,2,...,23): maximize \;\; obj = \sum_{q} (charge_{j,t,q}^{h} + discharge_{j,t,q}^{h}) \tag{5.4}$$

The charge and discharge action implemented by the TSO within one hour should satisfy the following constraints:

$$discharge_{j,t,q}^{h} \le RD_{j,t}^{h} \cdot b_{j,t,q} \tag{5.5}$$

$$charge_{j,t,q}^{h} \le RC_{j,t}^{h} \cdot (1 - b_{j,t,q}) \tag{5.6}$$

$$discharge_{j,t,q}^{h} \le regulation_{j,t,q} \cdot b_{j,t,q} \tag{5.7}$$

$$charge^h_{j,t,q} \le regulation_{j,t,q} \cdot (b_{j,t,q} - 1) \quad (5.8)$$

$$\begin{aligned} netaction^h_{j,t,q} = &\left(charge^w_{j,t} + charge^d_{j,t} + charge^x_{j,t} + charge^y_{j,t} + charge^h_{j,t,q}\right) - \\ &\left(discharge^w_{j,t} + discharge^d_{j,t} + discharge^x_{j,t} + discharge^y_{j,t} + discharge^h_{j,t,q}\right) \end{aligned} \quad (5.9)$$

$$E^h_{j,t,q} = E^h_{j,t,q-1} + \left(netaction^h_{j,t,q} \cdot y^h_{j,t,q}\right) \cdot \mu - \left[netaction^h_{j,t,q} \cdot (1 - y^h_{j,t,q})\right] \cdot \frac{1}{\mu} \quad (5.10)$$

$$\sigma_{j,t} = E^h_{j,t,qlast} - E^y_{j,t} \quad (5.11)$$

with $b_{j,t,q}$: binary indicating whether an upward regulation is taking place at quarter q of hour t ,day j; 1 if it is, 0 if not.

$charge^h_{j,t,q}$: amount of energy charged into the storage at quarter q of hour t ,day j in the hour-ahead auction [MW]

$discharge^h_{j,t,q}$: amount of energy charged into the storage at quarter q of hour t ,day j in the hour-ahead auction [MW]

$E^h_{j,t,q}$: energy level in the reservoir after the charge or discharge action at the end of quarter q of hour t , day j in the hour-ahead auction [MWh]

$regulation_{j,t,q}$: total volume required for the upward or downward regulation; positive if upward regulation, negative if downward regulation [MWh]

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

$\sigma_{j,t}$: net energy level shift at the end of hour t of day j after the actions taken within the hour t [MWh]

(5.5) and (5.6) indicate that the storage will discharge (or charge) only when the system needs upwards (or downwards) regulation and that the discharge or charge power should be less than the corresponding remaining capacity.

(5.9) calculates the net action after the hour-ahead use of storage. The energy level in the reservoir is related only to the final use of storage at the end of the considered auction.

(5.10) gives the energy level in the reservoir after the action taken in the hour-ahead auction.

(5.11) is used to count the net energy level change at the end of hour t with respect to the energy level established in the precedent auction.

As stated before, apart from the constraints listed above, we also need to ensure that there will be enough capacity in the following hours to offset the net energy level change at the end of hour t, and that this energy level change will not violate the energy level established in the previous auctions for all the following hours. The following constraints are constructed for this purpose.

Constraints (5.12) and (5.13) should be enforced if we assume that the TSO has perfect foresight of the regulation energy requirement during the whole period.

$$\forall j \in J : -RC^{h}_{j,24} \le \sigma_{j,23} \le RD^{h}_{j,24} \tag{5.12}$$

$$\forall j \in J, \forall t \in (1,2,...,23) : 0 \le E^{h}_{j,t,q} \le SE \tag{5.13}$$

(5.12) states that the net energy level change at the end of 23^{rd} hour should be able to be offset by the remaining capacity during the 24^{th} hour of the day.

(5.13) ensures that the energy level at any moment is between E_{max} and 0.

Constraints (5.14) and (5.15) should be enforced if we assume that the TSO has no foresight of the regulation energy requirement during the whole period.

$$\forall j \in J, \forall t \in (1,2,...,23), \forall k \in (t+1, t+2,...,24) : -\sum_{k=t+1}^{24} RC^{h}_{j,k} \le \sigma_{j,t} \le \sum_{k=t+1}^{24} RD^{h}_{j,k} \tag{5.14}$$

$$\begin{aligned}
&\forall j \in J, \forall t \in (1,2,...,23): \\
&0 \le \sigma_{j,t} + E^{y}_{j,t} \le SE \\
&0 \le \sigma_{j,t} + E^{y}_{j,t+1} \le SE \\
&... \\
&0 \le \sigma_{j,t} + E^{y}_{j,24} \le SE
\end{aligned} \tag{5.15}$$

(5.13) ensures that, for any action taken at time step, the net energy level change because of this action will not shift the total energy level above E_{max} or below 0 for all following hours.

IV. Discussion of results

This section presents a short discussion of the main results of the study. We have composed two auction-chains as presented in Figure 1.

- The first one is the combination of week-ahead, day-ahead and hour-ahead auction. The underlying storage's values are generation cost reduction, arbitrage value in spot market, and regulation energy supply.

- The second is the combination of day-ahead, first intra-day and second intra-day auction. The underlying storage's values are arbitrage value in spot market, congestion cost reduction and wind imbalance cost reduction.

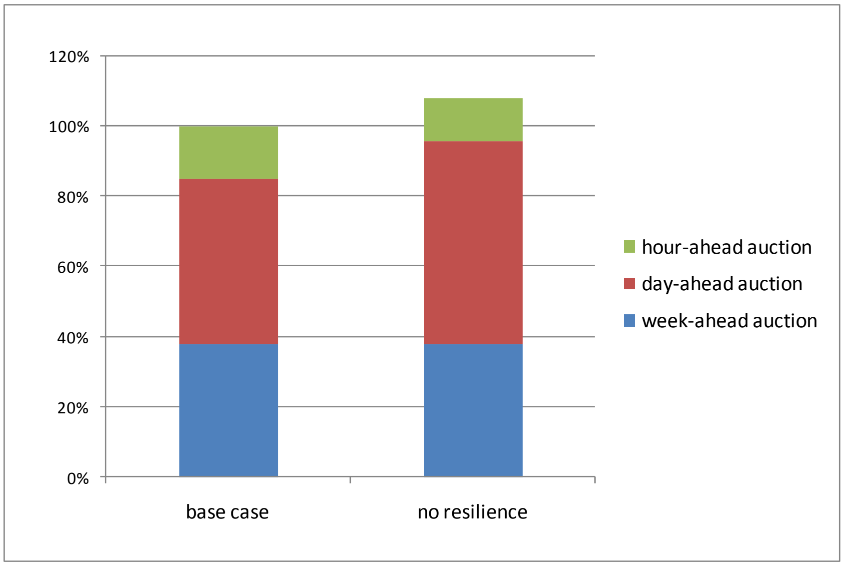
The input parameters used for each simulation is described in the Appendices.

A. results of the first combination of auctions

1. Importance of market resilience

The simulation results show that the arbitrage value of storage on the day-ahead market is quite sensitive to the depth or the resilience of the market, which indicates the price sensitivity due to an increase in offer or demand on the market. In the first combination of auction, the Belpex spot prices for the year 2007 are used to simulate the arbitrage strategy of the trader in the day-ahead auction. Figure 1 shows the share of storage's value for the whole year 2007 with resilience factor included and excluded. In the base case, we set the resilience factor to -0.01, which is consistent with the data published by Belpex. If we don't take into account the resilience factor, the day-ahead arbitrage value would be much overestimated (by around 15 % in the simulated case). It indicates that the resilience factor is an important issue to consider especially when we look for the optimal size of the storage unit. The advantage of having a high discharge capacity of the storage unit to benefit from the high prices will be discounted to some extent, as selling more energy in the spot market would lead to a decrease of the price. Consequently, the profit would be less than expected. This example provides evidence that he optimal operation or dimensioning of the storage unit is related not only to the price characteristics of market, but also to the resilience of the market.

Figure 9 Share of storage's value with and without resilience



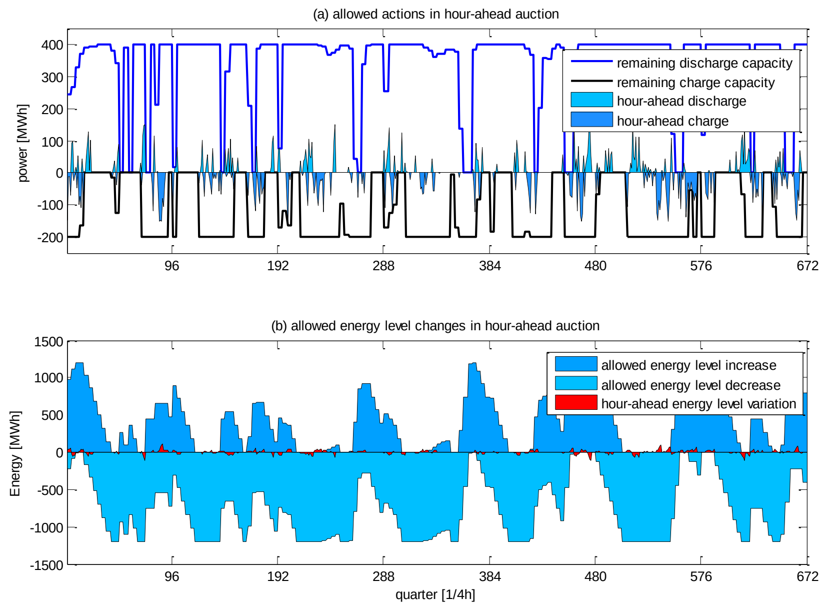
2. Necessity of the week-ahead auction

In the first combination of auctions, we have simulated the case of a supplier who uses storage to lower down his supply cost by economizing the part-load cost and start-up cost. The supplier has three power plants to meet the demand, one base-load, one intermediate-load and one peak-load unit. The demand that the supplier has to satisfy is obtained by scaling the Belgium electricity demand for the year 2007 to the total generation capacity of the supplier. We further assume that the supplier has perfect foresight of the demand for the whole week. The part-load efficiencies, the minimum up- and downtime limit, the ramping limit are taken into account in order to correctly estimate the storage's value in reducing the supply cost. However, we find that if we delete the week-ahead auction, most of the week-ahead value will be transferred to the day-ahead auction, which is the most lucrative part of the storage's value. It means that the week-ahead utilization of the storage and the day-ahead utilization of the storage is little complementary in the simulated case. This finding may question the necessity to carry out the week-ahead auction prior to the day-ahead auction.

3. Storage's capacity to provide regulation energy

The real regulation energy volume and price in Belgium during the year 2007 are used in the simulation of the hour-ahead auction. Given the small volume of regulation power required at each step of 15 minutes (generally between +/- 150 MW), the supply of regulation energy (both upwards and downwards) has a very minor effect on the energy level of the storage unit (see figure 10).

*Figure 10. Allowed actions in hour-ahead auction**



* the remaining charge, discharge and energy storage capacities are resulted from the week-ahead and day-ahead auction.

However, due to the limit of the remaining charge/discharge capacity, the storage is able to supply regulation energy only for 50% of time, which means the storage is not able to provide regulation energy systematically whenever the power system needs it. If we apply the stringent constraints on the verification process that assume no foresight on the regulation requirement, the use of the storage will be further reduced to 32%, and the saved regulation energy cost is halved in the simulated case. Hence, the storage unit could not be considered as being able to replace regulation reserve; it is only able to avoid activation of such regulation reserve in real time. In this sense, we can hardly expect storage unit to receive capacity payment for supplying regulation energy in real time.

B. results of the second combination of auctions

1. Limited contribution of storage in reducing the wind deviation cost

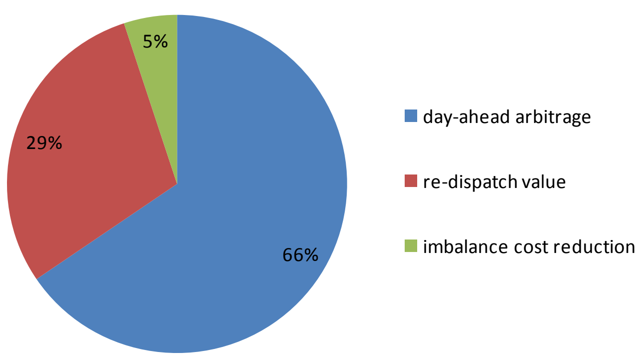
The share of storage's value in the second combination of auctions is presented in Figure 11. It can be seen that the storage's value in reducing the wind deviation cost is rather small as compared to other services. The deviation cost saving by storage is slightly higher in the Feed-in-Tariff scheme than in the market option in the simulated case, but they remain in the same order of magnitude. Several reasons may account for that:

First, although we can have a higher quality of wind forecast closer to the real time, the forecast error will never be reduced to zero. Therefore, even if the wind producer tries to converge to the newly made forecast, there will be inevitably a residual deviation that is subjected to the imbalance cost.

Second, in the simulated case, the new forecast is made for the whole period of the 24 hours next day, and the use of storage to converge to the new forecast is also optimized over this period. In this way, the wind forecast for the 24th hour of the next day is actually made at least 24 hours ahead, which may still lead to a relatively high forecast error. We may expect that adjusting the wind output just one or two hours ahead by the storage unit will reduce much more deviation cost than the method applied in the simulation. Such way of using storage to reduce wind deviation cost could be modeled similarly as the hour-ahead auction where the TSO uses storage to provide regulating energy.

Third, the low value of storage to reduce the imbalance cost is also related to the market rules and imbalance price characteristics. In the Spanish Feed-in-Tariff scheme, only the MWh that deviate 20% higher or lower of the real output is subject to the imbalance cost. Therefore, the contribution of storage in reducing the forecast error under the threshold of 20% is not counted. In the Spanish market option scheme, a penalty rate of 10% of current market price is applied to the net deviation volume. But the efficiency loss of the storage is also 10% for the charge process and discharge process separately. The market price difference between the charge time and discharge time should be sufficiently large in order to justify the use of storage.

Figure 11. Share of storage's value in the second combination of auctions

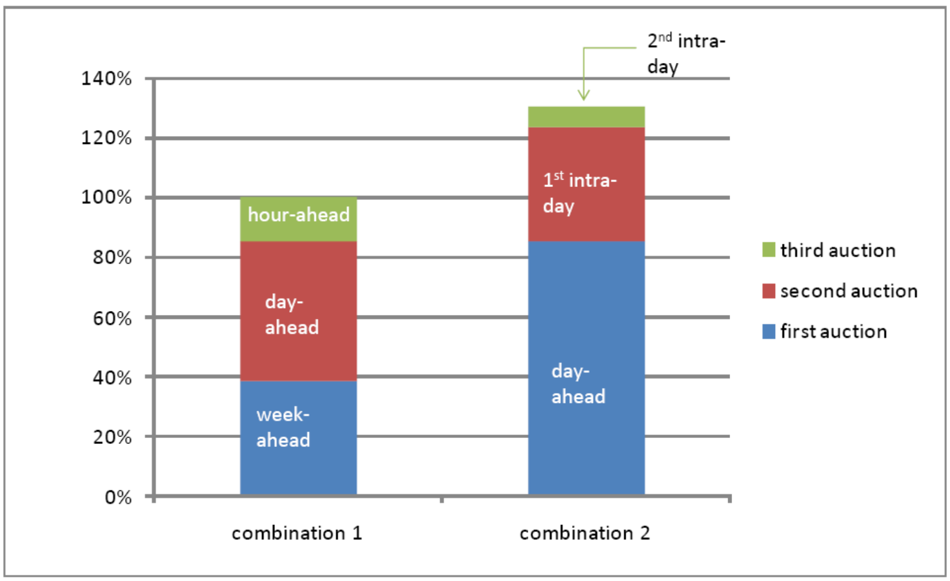


We simulate the use of storage to reduce re-dispatch cost in a fictive three-node electric system. Only one transmission line is set to be congested. The storage unit is installed at the node of load center, together with a peaking unit. The re-dispatch cost reduction by storage seems to be relatively high, especially when the network is heavily congested and when the market arrangement deviates from the optimal production scheduling resulted from a centralized cost minimizing optimization. A sensitivity analysis of the re-dispatch value of storage with respect to the transmission line capacity can be undertaken in the future.

3. Comparison between the first combination of auctions and the second combination of auctions.

In the second combination of auctions the day-ahead auction is launched in the first place. This allows capturing the arbitrage value of storage, which is the most lucrative part of value, with the full capacities of storage. Figure 5 presents a comparison between the two combinations of auctions for illustrative purpose. The day-ahead value of the second auction-chain is more or less the same as the sum of the week-ahead and day-ahead auction of the first auction-chain. Further more, the value of storage in reducing the re-dispatch cost and that in reducing the wind deviation cost are added to the arbitrage value of storage. Note that the share of storage's value for different service in different auction depends substantially on the input data parameter and the system set-up assumed in the simulation. Therefore, a direct comparison between the storage's values in different auction should be handled with caution.

Figure 12. Share of storage's value in different combination of auctions



V. Conclusion

The model proves that it is technically possible to coordinate the auctions of the right to explore the storage unit in different time horizon. While the day-ahead auction provides the biggest share of the storage's value, the other auctions create non-negligible additional values for the same storage unit. Thus, 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.

The model should be further completed and enriched in the following aspects:

First, more case studies should be undertaken in order to investigate the sensibility of storage's value with respect to the relevant market rules and market characteristics. A quick list of the influential factors for the storage's value includes the electric system characteristics, market price patterns, balancing requirement for wind generator, wind penetration rate, transmission capacity, etc.

Second, according to the preliminary simulation results, a combination of day-ahead auction (arbitrage value of storage in spot market), 1st intra-day auction (re-dispatch value), and hour-ahead auction (regulation value) may deliver a high total value of storage. This combination of auctions can be simulated in the further work.

Third, the capital cost of the storage unit can be integrated in the analysis in order to find out the optimal storage configuration within a specific market and regulatory environment. Such analysis may provide interesting evidence of how the optimal set-up of the storage unit could interact with the market and regulatory context of the electric system in order to maximize the value of storage.

Appendices

Appendix A. Simulation set-up in module A

The power plants information is given by Table 3.

Table 3. Power plants characteristics

plant	P_{max}	P_{min}	C^u	C^{p0}	C^{p1}	C^{p2}	ramp	mut	mdt
	MW	%	€	€/ MWh	€/ MWh	€/ MWh	%	hour	hour
plant1	700	350	100	17	12	14	60	6	6
plant2	400	120	50	40	30	35	80	2	2
plant3	200	40	0	80	70	75	100	1	1

Belgium electricity demand of 2007 is used for simulation.

Source: Elia

Appendix B. Simulation set-up in module B

Belpex Day-ahead spot market prices of 2007 are used for simulation.

Source: Belpex.

Appendix C. Simulation set-up in module C

Belgium regulation bids prices and regulation volumes of 2007 are used for simulation.

Source: Elia

Appendix D. Simulation set-up in module D

The power plants information is given by Table 4.

Table 4. Power plants characteristics(for re-dispatch model)

node	**plant**	P_{max}	P_{min}	C^u	C^{p0}	C^{p1}	C^{p2}	**ramp**	**mut**	**mdt**
		MW	%	€	€/ MWh			%	hour	Hour
1	Plant1	800	400	3000	17.5	12	14	60	6	6
1	Plant2	300	90	2000	40	30	35	80	3	3
2	Plant3	200	40	4	80	70	75	100	1	1
3	Plant4	400	120	2000	35	25	30	70	2	2
3	Plant5	150	75	4	74	65	70	100	1	1
3	Wind	1000								

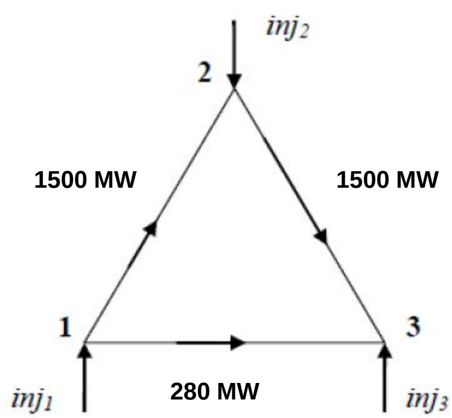
The storage unit is located in node 2.

The demand in each node is calculated by multiplying the load factor indicated in Table 5 to the total demand (real Belgium demand of 2007 scaled to the total generation capacity)

Table 5. Load information

Node	**1**	**2**	**3**
Load factor	0.2	0.5	0.3

Figure 3. Transmission line capacities



Appendix E. Simulation set-up in module E

No new input parameter.