Short-Term Optimization of Storage Power Plant Operation Under Market Conditions

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Abstract—**This paper deals with the optimization of storage power plant operation with a particular focus on market situation in the Latvian bidding area of the Nord Pool. Some currently already available storage options such as hydropower are considered, but attention is given to an emerging technology – hydrogen storage – as well. An algorithm for storage plant scheduling optimization is devised. In the case study, it is concluded that both technologies are capable of exploiting the price spread in the day-ahead electricity market. Another operational strategy apart from the price arbitrage is studied in this paper as well – cooperation with wind farms. Coordinated operation allows to decrease expenses caused by inaccurate wind generation forecasts.**

Keywords—energy storage; hydrogen; hydropower; optimization; pumped storage

I. Introduction

As of 2013 most of the electricity produced in Latvia is traded in the Nord Pool power market. It is the largest power exchange in Europe and combines the electricity markets of Nordic and Baltic countries.

In order to account for congestions in transmission networks, the Nord Pool is divided into several bidding areas (Fig. 1) where each country either has its own area or is separated into multiple zones.

Fig. 1. Nord Pool bidding areas

While most of the bidding areas are rather well integrated, the Latvian power system along with Lithuania has proven to be an exception. For instance, in 2015 the day-ahead (Elspot) prices after market clearing were the same in Latvia and its northern neighbor, Estonia, for only 34% of the hours, meaning that for the rest of the time the transmission capacity between these two countries was insufficient to assure efficient market coupling. On the other hand, Latvia and Lithuania are strongly interconnected – Elspot prices in both countries were the same for 99% of hours [1]. Essentially we can conclude that the Latvian and Lithuanian areas are somewhat isolated from the rest of the Nord Pool.

Furthermore, the lacking access to Scandinavian markets due to limited interconnections results in a constantly higher electricity price in Latvia and Lithuania than in the other bidding areas. The high prices can be explained by a lack of cheap generation sources. The Lithuanian power system has been in deficit since 2009 when the Ignalina nuclear power plant was decommissioned; the Latvian power system is a net importer as well, with the exception of spring flood season.

The above mentioned reasons illustrate the potential necessity for developing electrical energy storage options in the region. While the limited interconnectivity problem might be at least partially mitigated as further integration of the Baltic power systems into the European grid is realized (e.g., two new links were launched at the end of 2015 connecting Lithuania to Poland and Sweden; synchronization with the grid of Continental Europe is planned at some point in the future as well), these developments are likely to only increase the value of storage options, especially since the European Union is moving towards decarbonizing its economy.

One of the most widely implemented tools of decarbonization is increasing the share of renewable energy in the power sector. This introduces new issues for power system operators and market participants as a significant portion of the renewable energy sources are intermittent in nature, e.g., wind, solar and to some extent also run-of-the-river hydropower.

Even though the current penetration of wind and solar energy into Latvia and Lithuania is rather small (2% of the total electricity production in 2014 in Latvia and 17.5% in Lithuania), the trend is for the installed capacity to increase rapidly as shown in Fig. 2 [2], [3].

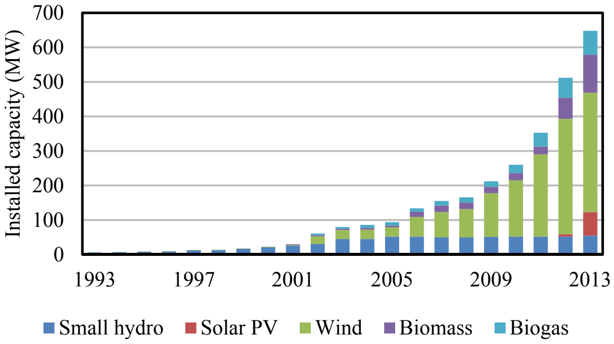

Fig. 2. Renewable energy sources in Latvia and Lithuania by capacity

For example, within 10 years the sum rated power of wind turbines in the region has grown from nothing to 348 MW.

The main contribution of this study lies in using real-life data of the Latvian power system to assess two different energy storage operation modes – price arbitrage and intermittent wind power accommodation under the existing electricity market conditions in the Latvian bidding area of the Nord Pool.

The second section gives a brief overview of the technologies studied in this paper, the third section explains the mathematical model, followed by the results and conclusions.

II. Storage Technologies under Study

A. Pumped Storage Power Plants

The oldest and most widely used power storage technology is pumped storage power plants (PSPP). They comprise about 99% of the electricity storage capacity in the world.

However, from countries participating in the Nord Pool only Norway and Lithuania have pumped storage capability. Besides, in Norway pumps are installed as addition to their large conventional reservoir hydroelectric power plants (HPPs) and the pumping/discharging cycle is seasonal in nature. However, the Kruonis PSPP in Lithuania is pure pumping type and schedules its operation on daily and weekly cycles.

The construction of new PSPP facilities is impeded by specific requirements for the site's location as a high difference between the elevation of lower and upper reservoirs is necessary to achieve an effective water head.

B. Hydrogen Storage

The idea of using hydrogen gas as a storage medium has gained a lot of attention lately in context of accommodating renewable energy. Hydrogen can be produced in the electrolysis process using either cheap off-peak electricity or excess power produced by intermittent sources.

Hydrogen can afterwards be stored in various forms, e.g., as a gas, liquid or within metal hydrides. It can be injected into the natural gas grid or contained in tanks for small- and medium-scale and underground for large-scale storage. The latter is especially interesting for the Latvian case as there exist several unique geological locations (Fig. 3) where gas storage might be possible in porous sandstone layers.

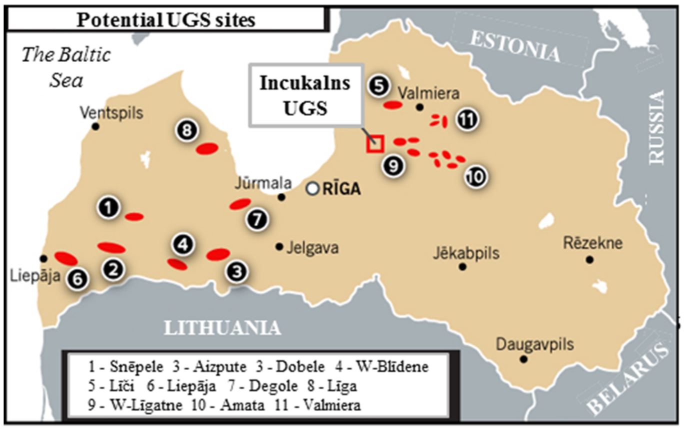

Fig. 3. Potential underground gas storage sites (in red) in Latvia [4]

One of these sites, Incukalns underground gas storage (UGS), is currently being used for natural gas storage while other sites are being investigated for the same purpose.

The hydrogen can later be used in industry, transport or converted back to electricity employing either fuel cells or gas turbines. In this paper we consider a hypothetical power-to-gas-to-power plant which uses electrolysis for hydrogen production and gas turbines for re-electrification.

C. Reservoir Hydropower

About half of the total installed generation capacity in Latvia is realized in a cascade of HPPs on the Daugava River. One of these plants, Plavinas HPP, is the second largest in the European Union by installed capacity. While not a storage option in the most traditional sense, reservoir HPPs without pumping capacity can provide similar services as conventional storage plants by regulating their production and accumulating water when generation is halted.

Granted, there are several constraints that limit the flexibility of reservoir HPP operation, namely, the risk of overflowing when inflow is large and, conversely, limited production capabilities when inflow is low.

III. Mathematical Formulation of the Optimization Problem

In this paper we consider two storage power plant operational strategies – firstly, a stand-alone storage plant benefiting solely from price differences in the day-ahead market (arbitrage) and, secondly, cooperation between intermittent energy producers (particularly, wind farms) and storage in order to balance discrepancies between the planned and actual generation from renewable energy.

A. Price Arbitrage in the Day-Ahead Market

The feasibility of exploiting price differences to gain profit in day-ahead markets largely depends on price dynamics in the particular market. For instance, researchers in [5] found that although a hypothetical PSPP could generate positive operational profits in all regions of Italy (MGP market), the net present value (NPV) of the future cash flows at the end of the project's lifetime was nevertheless negative in all cases. The authors explained it by the fact that even though peak prices in the MGP market are high compared to other European markets, the off-peak prices are comparatively high as well, resulting in an insufficient price spread.

The day-ahead market in the Netherlands (APX) is analyzed in [6]. The authors there have devised a strategy of using two different time horizons in storage self-scheduling – 24 hours for weekdays and 72 hours for weekends to account for the possibility of severely decreased prices during weekends. In our study, we have also covered the potential effect of weekends by extending the scheduling horizon to two weeks (336 hours) and using the results from the first 24 hours to submit bids to the market.

In [6], storage operation in price arbitrage mode is found to be profitable. The authors have also found a noteworthy peculiarity – the profits increase in correspondence to increased storage size (discharge duration), however, this effect stabilizes and eventually stops for discharge durations of about 24–26 hours. This conclusion holds true for all storage technologies (described by round-trip efficiencies) the authors considered.

The authors of [7] have assessed two different potential value streams for storage plants in Finland – price arbitrage in the Nord Pool Elspot market and participation in the balancing market. The authors identified that the electricity price was more volatile in the Finnish bidding area than in other Nordic countries sans Denmark. Nevertheless, [7] found the balancing market to be 3–6 times more profitable than the day-ahead market, depending on the storage technology.

In most of the studies, self-scheduling is implemented by means of linear programming (e.g., CPLEX linear solver [5]). In [8], [9] bilevel mixed integer linear programming models are devised. One drawback of the mixed integer approach is that charging and discharging at each hour has to be done either at full power or not at all, which does not allow for variability and thus limits the flexibility of operation.

Some other notable optimization methods used for storage power plant scheduling are dynamic programming [10] and evolutionary tristate particle swarm optimization [11].

A factor commonly found important is the effect stochastic parameters have on the optimal operation of storage plants, e.g., electricity market price when planning the day-ahead operation of a plant that aims to benefit from price arbitrage. In [12], AR, MA and ARIMA models are used for price forecasting and scenario generation. In [6], artificial neural networks (ANN) are used for this purpose. We also generally employ ANNs to forecast prices with the peculiarity of creating additional price prediction realizations by considering previous forecast errors. The forecasting process is laid out in more detail in our previous publications, e.g., [13].

In this study, the optimization problem of a closed loop storage plant operating on price arbitrage is described by a nonlinear objective function (1)–(2) and constraints (3)–(6). The studied power producer is assumed to be a price-taker and the price is exogenous to the optimization model, meaning that, in general, it can be provided by either of the previously mentioned forecasting tools or even from the actual price statistics, depending on the purpose of optimization.

The objective function is formulated as follows:

$$f\left(\Delta L, c\right) = \frac{1}{M}\sum_{m=1}^{M}\sum_{t=1}^{T}\left(P_t \cdot c_{m,t} - \left|P_t\right| \cdot om_{\text{var.}}\right) \to \max\,, \quad (1)$$

where ΔL – change in the amount of stored energy (MWh), P_t – power at hour t (MW), $c_{m,t}$ – electricity market price at hour t for realization m (€/MWh), M – number of realizations, T – length of the optimization horizon in hours, $om_{\text{var.}}$ – variable operation and maintenance (O&M) costs;

for

$$\begin{cases} P_t = -f\left(\Delta L_t\right)/\eta_{\text{acc}}, & \text{if} \quad \Delta L_t > 0 \\ P_t = -f\left(\Delta L_t\right)\cdot\eta_{\text{gen}}, & \text{if} \quad \Delta L_t \le 0 \end{cases} \quad \forall t \in T\,, \quad (2)$$

where $f\left(\Delta L_t\right)$ – a function that links the power generation and changes in the volume of storage medium (it depends on the technology being studied and can introduce nonlinearity), η_{acc} – accumulation efficiency, η_{gen} – generation efficiency;

subject to

$$\sum_{t=1}^{T}\Delta L_t = L_T - L_0\,, \quad (3)$$

$$-\sum_{t=1}^{S}\Delta L_t \le L_0 - \underline{L}\,, \quad (4)$$

$$\sum_{t=1}^{S}\Delta L_t \le \overline{L} - L_0\,, \quad (5)$$

$$P_t \in \left[\underline{P}_{\text{charg.}}, \overline{P}_{\text{charg.}}\right] \cup \left[\underline{P}_{\text{disch.}}, \overline{P}_{\text{disch.}}\right] \quad \forall t \in T\,, \quad (6)$$

where L_0 – initial storage level, $\underline{L}$, $\overline{L}$ – bounds on storage capacity, $S \in T$ – variable to enforce storage capacity bounds, $\underline{P}_{\text{disch.}}$, $\overline{P}_{\text{disch.}}$ – lower and upper limit on power in discharging mode, $\underline{P}_{\text{charg.}}$, $\overline{P}_{\text{charg.}}$ – lower and upper limit on power in charging mode (negative).

The model is implemented in MATLAB scripting environment which provides useful tools for solving various types of optimization problems. As (2) introduces non-smoothness in the objective function, gradient methods would not guarantee a correct solution. So we use the pattern search algorithm from Global Optimization Toolbox which is able to handle non-smooth and discontinuous functions [14].

B. *Cooperation with Wind Farms*

Some previous notable studies in the field of co-optimized wind and storage scheduling are found in [15]–[17].

Ref. [15] offers methodology to determine the optimal storage capacity to be added to wind farms. They conclude that the storage system rated power should be at least 20% of the wind farm power and the optimal charge/discharge duration for a 100 MW farm constitutes 4 hours.

In [16], particular focus is given to various hydrogen storage technologies that could be integrated with wind power in micro-grid applications. Methodologies to optimize the sizing, design and operation of storage to accommodate intermittent wind power are devised in both [16] and [17].

In this study, we have assessed the potential benefits of a storage plant operation based on balancing the discrepancies of the power sold in the day-ahead market and the actual wind power generation.

In Latvia, support for renewable generation is implemented through mandatory procurement, meaning that all the wind power produced is bought by a specially-created company (public trader) which in turn sells this power in the day-ahead market. In practice, it means that any deviations from the power offered in Elspot are handled not by the owners or operators of the wind farms but by the public trader instead.

Let us assume that the hourly income the public trader receives from selling the wind power can be expressed as follows:

$$R_t = \begin{cases} wp_{\text{real}.t} \cdot c_t, & \text{if} \quad \Delta wp_t = 0 \\ wp_{\text{pred}.t} \cdot c_t - \Delta wp_t \cdot cb_t^+, & \text{if} \quad \Delta wp_t > 0 \quad \forall t \in [1,24] \\ wp_{\text{pred}.t} \cdot c_t - \Delta wp_t \cdot cb_t^-, & \text{if} \quad \Delta wp_t < 0 \end{cases} \quad (7)$$

$$\Delta wp_t = wp_{\text{pred}.t} - wp_{\text{real}.t} \quad \forall t \in [1,24] \quad (8)$$

where $wp_{\text{real}.t}$ – actual produced wind power (MWh), $wp_{\text{pred}.t}$ – forecasted wind power (MWh) that was offered in the day-ahead market, Δwp_t – difference between the forecasted and actual wind power (MWh) (8), cb_t^+ – up-regulation price (€/MWh), cb_t^- – down-regulation price (€/MWh).

Essentially, this means that in case when the actual generation is lower than the planned generation, the trader receives less revenue than planned and additionally has to purchase the balancing power from the TSO. In the reverse scenario the trader sells its overproduction to the TSO at a price which is usually lower than the day-ahead market price.

If, however, the trader also has energy storage options, these negative effects can be alleviated:

$$P_t = \Delta wp_t \pm \Delta p_t \quad \forall t \in [1,24], \quad (9)$$

subject to constraints (3)–(6),

where Δp_t are the final deviations from the day-ahead generation plan that emerge if the storage constraints would otherwise be violated.

In this operational strategy the storage plant does not aim to exploit the day-ahead price arbitrage; it does, however, have to periodically purchase or sell energy in the market when the wind power forecasting errors have been largely one-sided in order to restore the state of storage to approximately 50%. This ought to be done each day (*d*) by registering the offset in storage level by the end of the previous day (*d* – 1) and bidding this amount in the next day (*d* + 1) market.

IV. Results and Discussion

A. Price Arbitrage in the Day-Ahead Market

The model presented in (1)–(6) is used to optimize the operation of storage plants of two different technologies (Table I) – pumped storage modeled using the characteristics of Kruonis PSPP and a hypothetical power-to-gas-to-power scheme that uses underground hydrogen storage as means of energy accumulation and realizes re-electrification with gas turbines (GT). The parameters of the second plant are assumptions based on general characteristics of polymer electrolyte membrane (PEM) electrolysis and GT equipment.

The day-ahead electricity market price for the case study (Fig. 4) is taken from the Nord Pool statistics for the Latvian bidding area, particularly, two weeks from September 21 to October 4, 2015 [1]. The results of the simulations are illustrated in Fig. 5–6.

TABLE I. Parameters of the PSPP and H_2 Plant

Parameters	Technology	
	PSPP (large-scale storage)	***Hydrogen (medium-scale storage)***
Nominal input and output power (MW)	900	25
Accumulation/ generation efficiency	0.8 (pump)/ 0.9 (turbine)	0.7 (PEM electrolysis)/ 0.6 (GT)
Storage capacity	10800 MWh	600 MWh[a]
Variable O&M costs	0.22 €/MWh [18]	1.7 €/MWh[b]

a. Underground storage capacity assumed to be sufficient for 24-hour discharge

b. Assumption made

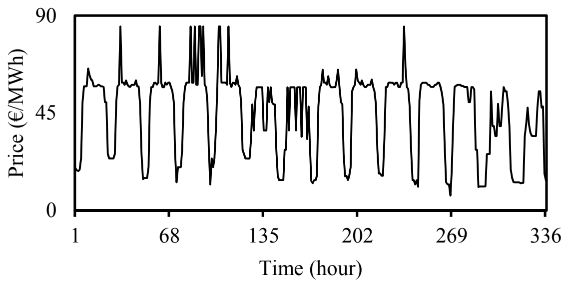

Fig. 4. Day-ahead electricity market price (Sept. 21–Oct. 4, 2015)

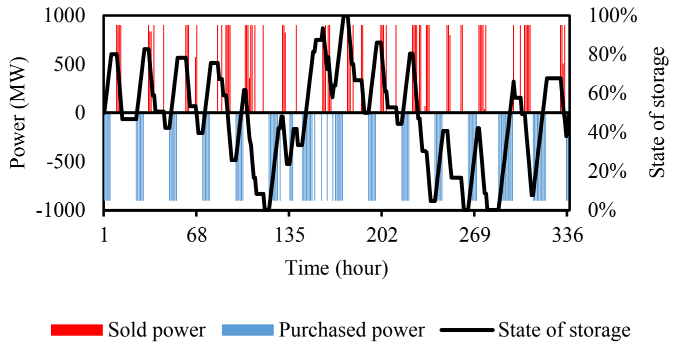

Fig. 5. Optimal schedule of the PSPP

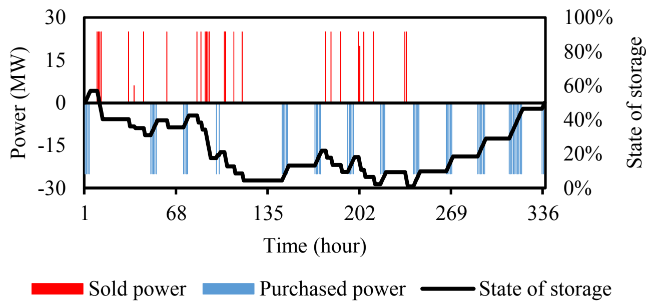

Fig. 6. Optimal schedule of the hydrogen (electrolysis/GT) facility

During the selected time horizon both stations manage to operate profitably. For the large-scale PSPP, the income from the sold electricity exceeds expenditure for the purchased power and variable O&M costs by 2.281 million €, whereas for the medium-scale hydrogen scheme this difference constitutes 20 869 €. The revenue is understandably smaller due to the smaller size of the proposed GT facility.

From Fig. 6 it can be concluded that the selected storage capacity of the hydrogen scheme is larger than necessary, as during the optimization horizon the volume of the stored energy never exceeds even 60% of the total capacity. Thus, the proposed model is useful in assessing the feasibility of various storage sizes for a storage plant.

B. *Cooperation with Wind Farms*

In order to assess the coordinated wind farm and storage operation scheme described in subsection III.B, we use statistics (Fig. 7–8) from the same time period as in the previous example.

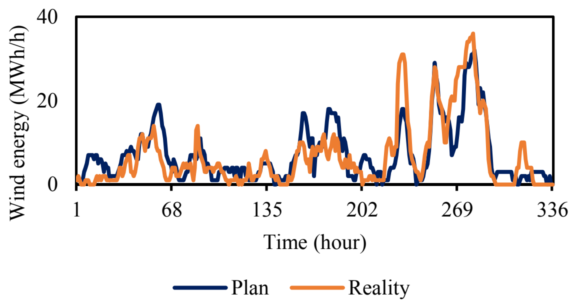

Fig. 7. Planned and actual wind energy generation (Sept. 21–Oct. 4, 2015)

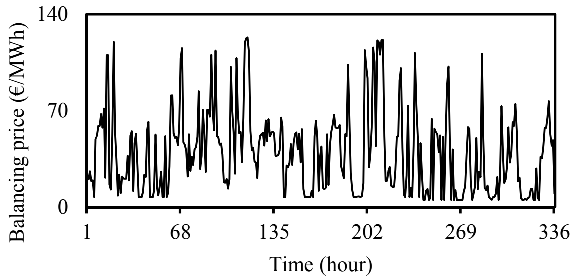

Fig. 8. Up-regulation price of the Latvian TSO (Sept. 21–Oct. 4, 2015)

If the forecasted wind energy production (Fig. 7) were accurate, the trader would receive 123 825 € revenue from Elspot during the two-week period under study. However, due to inaccurate predictions, the trader receives 89 183 € and has to pay 29 419 € for up-regulation, but it also earns 10 840 € for overproduced power netting 70 604 € in total revenue.

Now, let us consider a hydrogen storage plant as described in Table I operating in coordination with the wind farm. Fig. 9 illustrates the amount of energy the storage plant stores from excess wind generation and supplies to the market to balance insufficient wind generation, whereas Fig. 10 shows activities in the day-ahead market to maintain the state of charge at about 50%.

As a result of coordination, the wind and storage operation receives 122 630 € from bidding the forecasted wind generation in the day-ahead market; however, 27 750 € are spent to maintain adequate energy levels in the storage, additional 216 € are necessary to provide some minor balancing at times when the storage was insufficient and 2 262 € are received for selling unaccommodated wind energy production, finally, 4 197 € are costs associated with storage O&M. In total, the net revenue constitutes 92 729 €. Compared to the wind farm operation without storage, this results in an income increase of 22 125 €.

As established in IV.A, the opportunity cost of the hydrogen storage plant operating independently based on the day-ahead price arbitrage is 20 869 €, meaning that cooperation with wind farms might be capable of providing a better value. However, further studies should be conducted incorporating larger time frames to establish the potential benefits of such synergy throughout the lifetime of the power plants. Another area of future research is incorporating other generation sources in the coordinated dispatch.

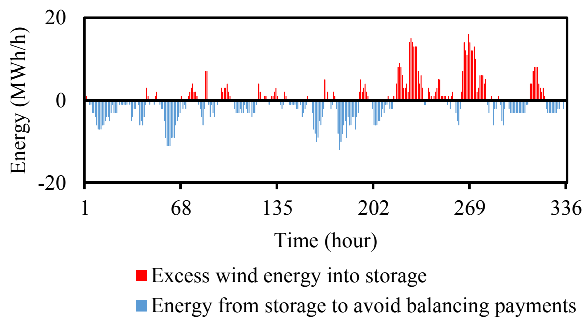

Fig. 9. Storage plant operations caused by wind generation imbalances

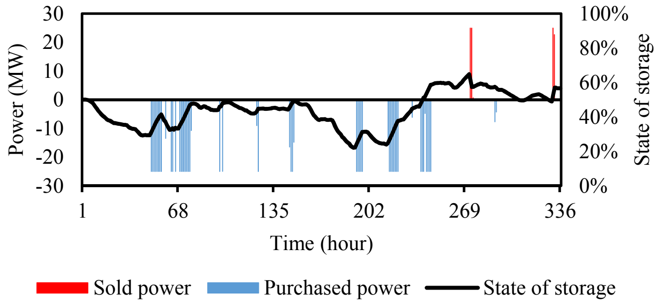

Fig. 10. Storage plant operations in Elspot to maintain charge

V. CONCLUSIONS

The simulations carried out using the proposed optimization model confirm that the day-ahead price profile in Latvia is sufficient for price arbitrage to provide a positive cash flow. This holds true for both considered technologies – pumped storage and hydrogen storage. The results this model provides could potentially be used as input data when evaluating the feasibility of a storage project's future operations.

The initially assumed hydrogen storage size corresponding to a 24-hour discharge duration proved to be unnecessary large for operation in the day-ahead price arbitrage mode as within the studied time period the state of charge did not exceed even 60% of the available storage capacity.

Finally, the coordinated participation of the wind power and storage plants in the day-ahead market was found to be beneficial for both the wind power traders and storage operators. In the time period considered this cooperation proved to provide slightly better net revenue than if the storage plant had operated independently. Furthermore, it offers additional environmental and societal benefits by avoiding wind power curtailment and making a maximum use of the available renewable energy.

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