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Hydropower Storage Optimization Considering Spot and Intraday Auction Market

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Abstract

This paper is a case-study based analysis of short-term hydro power optimization considering Spot and Intraday Auction markets. Both markets are closed order book auctions. The analysis shows that the usage of day-ahead price forecast-based water values in intraday trading leads to significantly different results than in the day-ahead market. This is because of the higher fluctuations and limited liquidity on the Intraday Auction market. A multistage quadratic optimization is presented that optimizes the Spot market dispatch on the first stage, and performs a post-optimization to exploit Intraday Auction optionalities on the second stage. The limited liquidity on the Intraday Auction market is accounted for. A case study based example is given and optimal production schedules and bidding strategies are calculated. Further, it is presented why different water values are needed for different markets and how they can be used in the practical short-term position management.

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Keywords: pumped hydro storage, renewable integration, Spot market, Intraday Auction, hydro scheduling in multiple power markets

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1. Introduction

With the so called "Energiewende" the conditions on the German energy market have changed fundamentally. A lower price level but most notably the flattened regular price spread between peak and off-peak have influenced the profitability of pumped hydro storage power plants. Furthermore, to lessen the effects of production deviations during the intraday, the German government introduced a quarter-hourly Intraday Auction market that takes place at 3pm day-ahead. We present a multi-stage quadratic optimization approach to address the challenges of the markets. After giving a short overview on the literature in 1.1 the market environment for pumped hydro power plants is addressed in 1.2 and the new Intraday Auction is discussed in 1.3. In chapter 2 the optimization approach is presented. In 2.1 the first stage optimization is outlined, followed by 2.2 and the extensions that have been made to consider the quarter-hourly Intraday Auction market and liquidity. We conclude with a case-study example in chapter 3.

1.1. Literature review on short-term hydro storage optimization

The literature on solving hydro power storage scheduling problems can be separated into two general categories. On the one hand, the literature follows a system economic approach: e.g. Oliviera et al. (1993) solve a mixed integer linear program in a system context and integrate cost-efficient storage capacity. On the other hand, several papers focus on the individual plants and on how to operate a singular or a portfolio of hydro storages. These approaches are mainly based on using wholesale electricity prices and calculating an optimal control strategy. The latter approach usually separates the optimization between daily pumped hydro power storages with small reservoirs and seasonal hydro power storages with large reservoirs and relatively small machines in comparison to their reservoir size. The major literature on seasonal hydro storages focuses on improving the optimization methods. Wallace et al (2003) introduce stochastic programming models in energy. A literature review on reservoir operation optimization is given by Labadie (2004). Significant mathematical contributions have been done by Pereira et al. (1991) introducing a SDDP approach, which has been extended by Löhndorf (2013) including stochastic prices and inflows in one probability distribution and Shapiro et al. (2013) in terms of risk averse optimization. Abgottspon et al. (2012 and 2013) includes the long-term future and the hourly day-ahead market into one optimization and discusses the influence of a price maker. The influence of the Intraday Continuous market on storage evaluation has been pointed out by Dogan (2013). The used optimization model has been introduced in Braun (2015). An overview on the changes on the German energy market and future developments is given in the "Grünbuch" (BMWi 2015) published by the German government.

1.2. Market environment for pumped hydro storages

Due to the extensive expansion of the installed capacity of renewable energies, the market conditions in Germany have changed. Three different effects can be observed on the German energy market: Firstly, energy prices have dropped because renewable energy sources (RES) with low variable costs entered the Merit Order. Secondly, the classical peak-off-peak price profile fluctuates as photovoltaics (PV) generation adds supply particularly during midday and thus prevents the historical peak prices around noon. Thirdly, long periods with substantial wind feed-in are causing low-price periods with increasing frequency. Nevertheless, the production capacity of conventional power plants has remained nearly unchanged, which leads to a lack of scarcity prices in the energy only markets that would allow more expensive conventional generation to cover their costs. An overview on the price development on the various energy-only markets can be seen in Tab.1. This situation influences the position management of all existing power plants. The dispatch of seasonal hydro power storages in the short-term is steered by water values from a mid- and short-term optimization. These water values in turn are calculated using inflows and price forecasts. The latter is usually based on a price forward curve for the day-ahead market and an appropriate stochastic to model the fluctuations. Using the water values, bids are set up to trade the energy of the hydro power plants on the day-ahead market. After the auction has cleared the remaining flexibility can be traded on the Intraday markets. To generate offers for the various markets, normally, the same water values are used. Since the specifics of the 15 min Intraday markets have not been considered we present an approach below.

Table 1: Price development on the German energy markets. Data received from European Power Exchange 2015

		Spot Auction 1h	Intraday Auction 1/4h	Intraday Continuous 1h	Intraday Continuous 1/4h
	2012	42.85 €/MWh		43.87 €/MWh	35.21 €/MWh
yearly	2013	37.78 €/MWh		38.42 €/MWh	37.76 €/MWh
average	2014	32.76 €/MWh	27.68 €/MWh	33.01 €/MWh	32.59 €/MWh
prices	2015	30.46 €/MWh	30.46 €/MWh	30.78 €/MWh	30.95 €/MWh
	all years	36.57 €/MWh	30.17 €/MWh	37.15 €/MWh	34.55 €/MWh
	2012	18.90 €/MWh		20.22 €/MWh	28.79 €/MWh
yearly	2013	16.46 €/MWh		17.98 €/MWh	23.54 €/MWh
standard	2014	12.77 €/MWh	17.83 €/MWh	13.72 €/MWh	18.81 €/MWh
deviation	2015	12.61 €/MWh	15.56 €/MWh	13.01 €/MWh	16.93 €/MWh
	all years	16.32 €/MWh	15.83 €/MWh	17.52 €/MWh	23.13 €/MWh
average volume traded	first 200 days of 2015	25,554 MWh	429 MW	2,882 MWh	474 MW

1.3. Quarter-hourly Intraday Auction

As a consequence of the current market situation, politics and the German federal network agency (BNetzA) worked on improving the market conditions and introduced, in addition to the already existing day-ahead Spot Auction, the quarterly and hourly Intraday Continuous markets, the quarterly Intraday Auction as a fourth market in Dezember 2014. Therfore, the prices of 2014 are not representive. However, the name Intraday Auction can be misinterpreted: the Intraday Auction takes place at 3pm day-ahead (European Energy Exchange 2015). The average volume traded per day during the first 200 days of 2015 were 429 MW on the Intraday Auction in comparison to 25,554 MWh in the Spot market, see Tab.1. The average price level between Intraday Auction and Spot market are nearly identical which is why it is reasonable to assume that the markets are arbitrage free. Generally it can be seen that the shorter the period till delivery the higher the average price level.

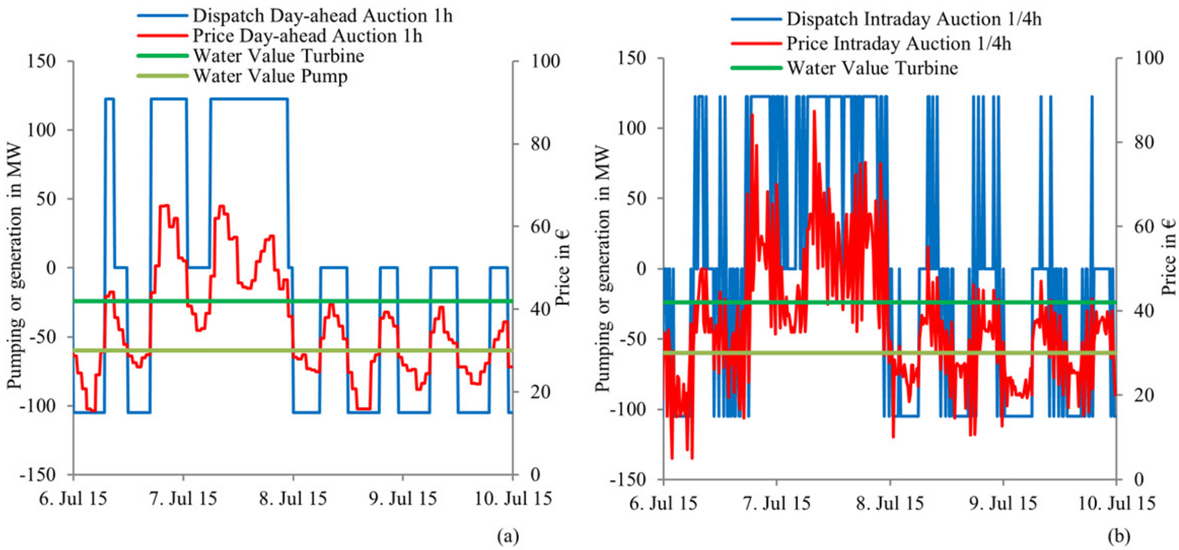

Fig. 1 Exemplary dispatch of a seasonal hydro power storage power plant on the Spot (a) and the Intraday Auction market (b)

In Fig. 1 an exemplary dispatch of a seasonal hydro power storage plant is pictured. Assuming a water value for water release of 42 €/MWh and pumping of 30 €/MWh, the figure shows that energy is generated when the price is above the water vlaue und energy is consumed as long as the price is below the pump water value. This is the case for part (a) using the historic day-ahead Spot price and as well for part (b) using the day-ahead Intraday Auction price, which is quarter-hourly based. Generally the price spreads as wells as the total generation and pumping time are higher in the Intraday Auction. Furthermore, the machine is switched 17 times from pump to generation mode during the 7 days when dispatched according to the Spot market. When traded on the Intraday Auction the machine is switched 129 times from pumping to generating mode.

2. Trading hydro storages on the Spot and the Intraday Auction market

As discussed in Braun (2015) the evaluation of hydro power storages on the German electricity market highly depends on the chosen input factors and the optimization method itself. The most important value drivers identified were market prices, followed by balancing energy provision, the optimization model itself and inflows. Therefore it seems promising to integrate more than one market in the hydro power storage optimization, as has been done, e.g. with the Spot and the Balancing energy markets. Ideally this should include the Spot, Intraday Auction, Intraday Continuous and the Balancing energy markets:

$$\boldsymbol{Revenue} = \boldsymbol{Revenue}\ (\boldsymbol{Spot} + \boldsymbol{Intraday\ Auction} + \boldsymbol{Intraday\ Continious} + \boldsymbol{Balancing\ energy}) \quad (1)$$

Nevertheless, the optimization throughout markets is rather complicated since time, pricing structure, incentives, and the desired control parameters vary. We used a multistage mid- to short-term model and focus on the optimization of the hydro power dispatch on Spot and Intraday Auction markets to determine the optionalities of the short-term. This means that we do not consider balancing energy provision, stochastic price forecasts, or stochastic inflows. We do consider grid charges, efficiencies, quarterly and hourly time steps, Spot prices, Intraday Auction prices, cascaded plants, daily pumped hydro power storages, seasonally pumped hydro storage, reservoirs without pumps, ten years average inflows, hydraulic short circuit and spillage.

The equations of the optimization problem are defined using the following symbols:

- $s \in S = 1, \dots, W$: reservoir
- $w \in W = 1, \dots, W$: machine
- $w \in \underline{sw}$: machine w below reservoir s
- $w \in \underline{ws}$: machine w above reservoir s
- $t \in T = 1, \dots, T$: time stages hourly and quarter-hourly
- $\mathrm{N}_{t,w}/v_{t,w}$: Grid charges of machine w at time stage t
- PFC_t: Spot Auction market price
- $PFC_t^{short-term}$: Intraday Auction market price
- $SV_{s,t}$: losses or spillage of reservoir s between time stage t and t+1
- $SVmax_{s,t}$: maximum losses or spillage of reservoir s between time stage t and t+1
- $SQ_{s,t}$: filling level of storage s at time stage t
- $SQin_{s,t}$: inflow reservoir s between time stage t and t+1
- $SQstart_s$: start reservoir level s at the first time stage
- $SQend_s$: target reservoir level s at time stage T
- μ_W: efficiency of control energy
- $PWT_{w,t}$: turbine use of machine w at time stage t
- $PWP_{w,t}$: pump use of machine w at time stage t
- $PWT_{w,t}^{short-term}$: power sold on the Intraday Auction of machine w at time stage t
- $PWP_{w,t}^{short-term}$: power bought on the Intraday Auction of machine w at time stage t
- $Sell_{w,t}$: power sold on the Spot Auction of machine w at time stage t
- $Buy_{w,t}$: power bought on the Spot Auction of machine w at time stage t
- $PWmaxT_w$: maximum turbine power of machine w

- $PWmaxP_w$: maximum pump power of machine w
- $QWmaxT_w$: maximum flow rate turbine of machine w
- $QWmaxP_w$: maximum flow rate pump of machine w

The multistage optimization is explained in the following. In 2.1 the general optimization problem is introduced, aiming to find an optimal production schedule and water values for the day-ahead Spot market. In 2.2 the model has been extended to use the already existing hourly optimal production schedule as an input and post-optimize on the quarter-hourly Intraday Auction market. Water values and a final production schedule are generated.

2.1. First stage: Spot optimization

The first stage optimization problem has an hourly time resolution: $t = 1h, .., 8760h$. For the profit maximization problem the spread between generation and pumping price as well as the absolute height of the price is important. The profit is summed up over the time and the machines consisting of pumps and turbines. The objective function can be stated as follows:

$$\max_{\substack{PWT \\ PWP}} Profit \tag{2}$$

$$Profit = \sum_{\substack{w \in W \\ t \in T}} \mathrm{PFC_t} \cdot \left(\mathrm{PWT_{t,w}} - \mathrm{PWP}_{t,w}\right) - \mathrm{N}_{t,w} \tag{3}$$

The most important constraints of the optimization problem are the reservoir balancing equations for every reservoir in the cascade. The filling level in t is a summation of the filling level in $t-1$ and the water that has been released from an upper reservoir and subtracting the water that has been released into a lower reservoir. s denotes the reservoirs and w the machines at time stage t. $\underline{sw}$ indicates that the machine is located below a reservoir. $\underline{ws}$ marks the machines that are located above a reservoir.

$$SQ_{s.t} = SQstart_s; \;\; s \in S, t = 1 \tag{4}$$

$$SQ_{s,t} = SQ_{s,t-1} + SQin_{s,t} - SV_{s,t} - \sum_{w \in \underline{SW}} \left(\frac{PWT_{w,t}}{PWmaxT_w \cdot QWmaxT_w}\right) + \sum_{w \in \underline{WS}} \left(\frac{PWP_{W,t} + R_{W,t}}{PWmaxP_w \cdot QWmaxP_w}\right); \; s \in S, t \in 2, \ldots, T \tag{5}$$

The reservoir filling levels have to be within the limits that are given by the following equations.

$$SQ_{s,t} \geq SQmin_{s,t}; \quad s \in S, w \in W, t \in T \tag{6}$$

$$SQ_{s,t} \leq SQmax_{s,t}; \quad s \in S, w \in W, t \in T \tag{7}$$

The target filling level is variable. A good way to set the end filling level is to optimize over more than one year and to use the intermediate result as end filling level of the short term optimization.

$$SQ_{s,T} = SQend_s; \quad s \in S \tag{8}$$

The spillage is limited by $SVmax_{s,t}$.

$$SV_{s,t} \leq SVmax_{s,t}; \quad s \in S, t \in T \tag{9}$$

The pumping and the turbine power are determined by the machine characteristics.

$$PWP_{w,t} \leq PWPmax_w; \quad w \in W, t \in T \tag{10}$$

$$PWT_{w,t} \leq PWTmax_w; \quad w \in W, t \in T \tag{11}$$

The grid charges are considered as follows:

$$\mathrm{N}_{t,w} = \max \; \left(0, PWP_{w,t} - PWT_{w,t}\right) \cdot v_{t,w} \tag{12}$$

Further inequality constraints are:

$$0 \leq SV_{S,t}; \quad s \in S, t \in T \tag{13}$$

$$0 \leq PWT_{W,t}; \quad w \in W, t \in T \tag{14}$$

$$0 \leq PWP_{W,t}; \quad w \in W, t \in T \tag{15}$$

$$0 \leq SQ_{S,t}; \quad s \in S, t \in T \tag{16}$$

2.2. Second stage: Intraday Auction considering liquidity

The second stage is a post-optimization with quarter-hourly time resolution with $t = 1qh, \ldots, 35040qh$. The Spot market can be seen as a sufficiently liquid market. However, when considering the other energy only markets it is crucial to take market liquidity into account. This means that it is normally not possible to trade a desired quantity at a given price. To determine a liquidity factor for the quarter-hourly Intraday Auction is subject of current research. Not knowing the correct liquidity factor we assume 1 €/100 MW, based on practical experiences, as a rough but good approximation. The suggested liquidity factor depends on the amount traded. Therefore the optimization problem of chapter 2.1 transforms into a quadratic problem:

$$Profit = \sum_{\substack{w \in W \\ t \in T}} \Big[\big(PFC_t^{short-term} - PWT_{w,t}^{short-term} \cdot 0.01 \big) \cdot PWT_{w,t}^{short-term} - \big(PFC_t^{short-term} + PWP_{w,t}^{short-term} \cdot 0.01 \big) \cdot PWP_{w,t}^{short-term} - \mathrm{N}_{t,w} \Big] \tag{17}$$

The optimal production schedule of the first stage optimization is used as an input parameter for the second stage model. $PWT_{t,w}$ is set as $Sell_{w,t}$ and $PWP_{t,w}$ is set as $Buy_{w,t}$ to show that they have already been traded on the Spot Auction. In the trading equation (18) this information of the upstream optimization is used. The final production $(PWT_{w,t} - PWP_{w,t})$ therefore depends on the amount already traded and the amount that is traded on the short-term Intraday Auction market.

$$PWT_{w,t} - PWP_{w,t} = Sell_{w,t} - Buy_{w,t} + PWT_{w,t}^{short-term} - PWP_{w,t}^{short-term} \tag{18}$$

All further equations need to be adjusted in terms of time resolution and physical hydro management restrictions.

3. Example

For this example, the problem has been implemented as a multistage quadratic optimization in the optimization software GAMS (General Algebraic Modeling System). To illustrate the results of the presented optimization a calculation from January 1st 2015 to April 30th 2015 has been performed using the historic Spot and Intraday Auction prices. An exemplary price profile for a week and a day in January can be seen in Fig. 2.

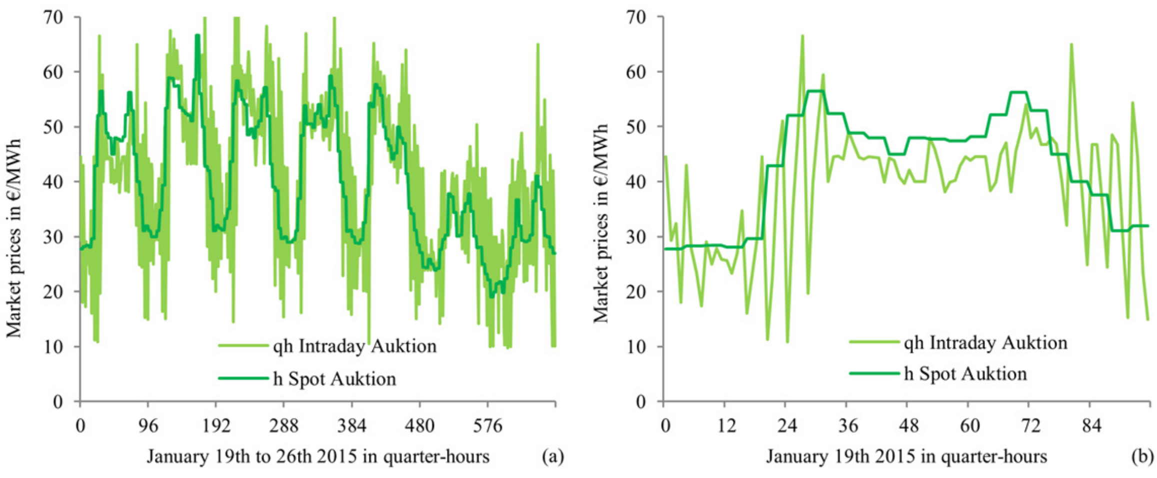

Fig. 2 Exemplary hourly Spot and quarter-hourly Intraday Auction price curves: (a) one week in January (b) one day in January

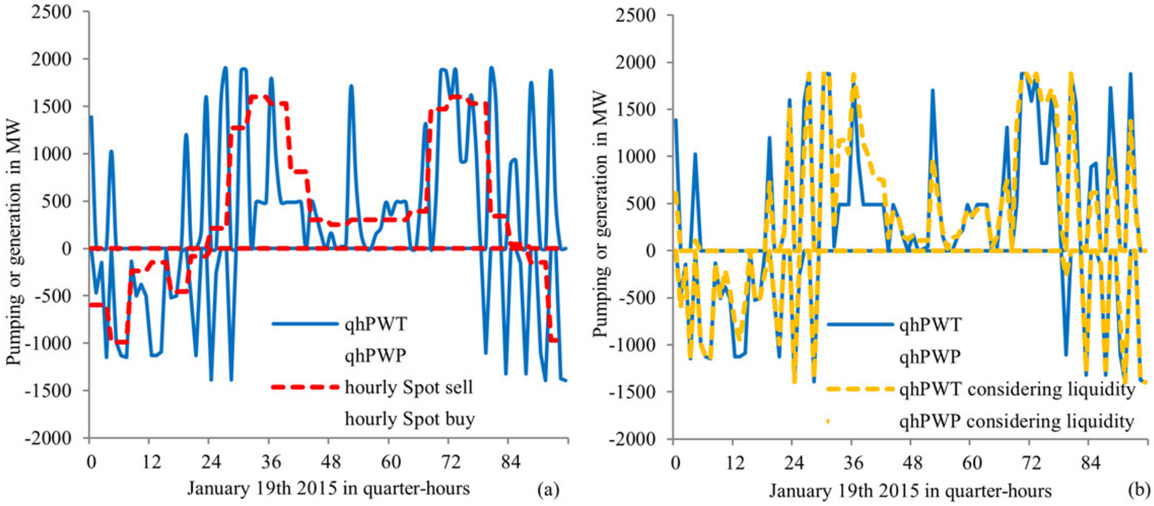

Fig. 3 (a) Comparing the production schedule of the first stage optimization for the Spot Auction in red with the production schedule of the post-optimization for the Spot and the Intraday Auction in blue (b) Comparing the post-optimization production schedule for the Spot and the Intraday Auction without (blue) and with the consideration of liquidity (yellow)

The optimization has been applied on a real world large-scale hydro storage portfolio with more than 20 reservoirs, about 2 GW pump power and 3 GW generating power. Every machine is defined by an efficiency rate, gird charges, flow rate, hydraulic short circuit ability, minimum and maximum capacity. Furthermore, the portfolio is a mix of large reservoirs for seasonal and small reservoirs for daily storage including inflows. Following the introduced multistage optimization, the first stage uses the day-ahead Spot Auction prices to determine an optimal production schedule. This production schedule is presented in Fig. 3 (a), denoted by the red line. The second stage optimization is a post-optimization that adjusts the production schedule based on the quarter-hourly Intraday Auction prices. The hourly Spot Auction production schedule is input for the second stage optimization and is considered as a sell or a buy position that has to be yielded. Based on the already existing position, the model buys or sells energy on the Intraday Auction market within the physical limits of the power plants. The combined sales or buys are not allowed to exceed the total capacity of the pumps or turbines in the hour as well as the quarter-hour. The blue line in Fig. 3 (a) presents the resulting production schedule combing the sell and buy positions of both markets. This is possible since the hydro power machines are highly flexible and can be switched off and on for single quarter-hours. The extensive changes of the production plan after the second stage optimization are a consequence of the high price fluctuations on the Intraday Auction market as can be seen in Fig. 2. In some quarter-hours the complete delivery position of the Spot Auction is repurchased on the Intraday Auction market. Beyond, more energy is bought on the Intraday Auction to use the pumps and store water. This behavior can be seen especially in the morning and the evening when the price level changes.

In the introduction, a table was presented with the average quantities traded on the different energy markets. Whereas more than 25 GW are traded every hour on the Spot market just 0.5 GW are traded quarter-hourly on the Intraday Auction market. As explained above it is not unusual for a large-scale power plant operator to try to sell or buy more than 0.5 GW. In the presented large scale case study even more than 2 GW of energy per quarter-hour are traded. We solved the liquidity problem using a liquidity discount of 1€/100MWh traded. The result can be seen in Fig. 3 (b). The final production plan considering both markets and liquidity discount is outlined in yellow and without liquidity in blue, just as in (a). In some quarter-hours the quantities traded are significantly reduced or increased. Nevertheless, including the Intraday Auction Market into the optimization doubles the calculated profit of the system. After presenting the effects of the optimization spanning two markets on the optimal production schedule, the impacts on the water values need to be discussed. Assuming a perfect market including no-arbitrage and full liquidity as well as unlimited upper and lower reservoirs, the water values for both markets should be the same. But none of these assumptions hold true in our real world application. Therefore we determine the water values from the dual variables of the reservoir balancing equations which is reasonable for seasonal hydro storages. Since the optimization was performed in a two stage optimization, the water values for the first and the second stage could be easily calculated. For this case-study, the water values of the seasonal hydro storages for the Intraday Auction market were about 2 to 5 €/MWh higher as the water values for the Spot Auction. This is because of the fluctuating Intraday Auction prices (higher spreads) and limited lower basins. When considering liquidity, the water values decrease about 0.2 to 1 €/MWh in comparison to the case without liquidity. The latter is reasonable since on the one hand the amount traded is reduced, see Fig.3 (b) and on the other hand the realized price is lower because of the limited liquidity. Such water values can be used in every-day business as shadow prices to determine the short-term position management. Therefore, to compute different water values for various markets has great potential for improving the hydro power dispatch. The portfolio calculation took two minutes using Intel Core i5 CPU and 4 GB memory size and is therefore suitable for real operation. Calculating liquidity factors is subject of current research.

4. Conclusion

In this paper optimal bidding strategies are outlined for seasonal hydro storage power plants in a competitive electricity market considering the perspective of a storage operator and the difficult current market conditions in Germany. An analysis shows that the usage of day-ahead price forecast-based water values in intraday trading leads to a significantly different usage of the hydro storages than intended for the day-ahead market. This is due to higher fluctuations and limited liquidity on the Intraday Auction market. A multistage quadratic optimization approach is presented that accounts for both: markets and liquidity. On the first stage of the optimization the day-ahead Spot Auction market is considered by calculating water values and an optimal production schedule. This schedule is in turn used as an input for the second stage optimization, where a post-optimization is performed using the quarter-hourly Intraday Auction prices. The high fluctuations as well as the limited liquidity of the quarter-hourly market are addressed. The water values and a production schedule are calculated for the Intraday Auction market. The model has been tested in a real-world case study. The two stage optimization exploits the optionalities within the markets. Since the power plants are used on both markets the profit doubles in comparison to just considering the Spot Auction Market. To realize the planned additional profit optimal production schedules and water values for both the Spot and the Intraday Auction market are calculated. The exemplary results show that the water values for the Intraday Auction market are higher than the ones for the Spot market because of the fluctuating Intraday Auction prices and limited lower basins. Considering several markets when optimizing the hydro storage dispatch is crucial for the practical short-term position management.

References

[1] Oliviera, P., McKee, S., Coles, C. Optimal scheduling of a hydro thermal power generation system. European Journal of Operational Research 71, 334–340; 1993

[2] European Power Exchange, Intraday Auction and Market Data, https://www.epexspot.com/en/product-info/intradayauction; 2015-09-01

[3] Pereira, M., Pinto, L. Multi-stage stochastic optimization applied to energy planning. Mathematical Programming, 52, 359–375, 1991

[4] Labadie, J. Optimal operation of multi reservoir systems: State-of the- art review. Journal of Water Resources Planning and Management 130, 2, 293–111, 2004

[5] Wallace, S., Fleten, S. Stochastic programming models in energy. Stochastic Programming, Handbooks in Operations Research and Management Science, A. Ruszczynski and A. Shapiro, Eds. Elsevier, vol. 10, 637 – 677, 2003

[6] Shapiro, A., Tekaya, W., Costa, P., Pereira, S. Risk neutral and risk averse Stochastic Dual Dynamic Programming method. European Journal of Operational Research 224, 375–391; 2013

[7] Löhndorf, N., Wozabal, D., Minner, S. Optimizing Trading Decisions for Hydro Storage. Systems using Approximate Dual Dynamic Programming. Working Paper, Operations Research, 61 (4), ISSN 1526-5463, 2013

[8] Abgottspon, H., Bucher, M., Andersson, G. Stochastic dynamic programming for unified short and medium-term planning of hydro power considering market products. 12th IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), 2012

[9] Abgottspon, H., Andersson, G. Stochastic scheduling for a price-maker hydro producer considering forward trading, Conference Paper, PowerTech IEEE Grenoble. 2013

[10] Dogan, K. Uncertainties in energy markets and their consideration in energy storage evaluation. Vol. 4. KIT Scientific Publishing, 2013

[11] Braun, S. Herausforderungen und Komplexität der Wasserspeicheroptimierung. IEWT Internationale Energiewirtschaftstagung, 1-17, Wien, 2015

[12] Bundesministerim für Wirtschaft und Energie (BMWi) Ein Strommarkt für die Energiewende, Grünbuch 2015, http://www.bmwi.de/DE/Mediathek/publikationen,did=666660.html; 2015-09-02