# Stochastic multistage bidding optimisation in an intraday market with limited liquidity

Edda Engmark
Hanne Sandven
Stein-Erik Fleten
Norwegian University of Science and Technology
Dept. of Industrial Economics and Technology Management
Trondheim, Norway
edda.engmark@accenture.com, hanne.sandven@powel.no, stein-erik.fleten@ntnu.no

Gro Klæboe
Powel AS
Trondheim, Norway
Email: gro.klaeboe@tronderenergi.no

***Abstract*—This paper describes a multistage stochastic mixed integer programming problem for a hydro power producer that maximizes profit in the low liquid intraday market and balancing market. A comprehensive modelling framework with an internal rolling horizon is presented and the continuous intraday market is modelled using stochastic residual demand curves.**

***Index Terms*—Operations Research, Power Generation Economics, Economic forecasting, Profitability.**

## I. INTRODUCTION

A producer with dispatchable assets, such as a hydro power producer, can offer its flexibility in multiple markets, which makes the decision process complex. This article models a Nordic hydro power producer, and the post-spot trade-off between the multilateral intraday market (IM), a continous double auction, and a marginal priced balancing market (BM) without capacity reservation.

We offer a complete framework to formulate a post-spot trading strategy, as well as a tool to quantify the value of participating in the IM. Similar to [3], [4] and [5] a detailed technical description of hydro power production. In line with [1], and opposed to [6] and [7] the limited liquidity in post spot markets is modelled in comprehensive detail. The IM liquidity is described using residual demand curves, inspired by [2] who applied the methodology to a centrally cleared intraday market. Price drivers for the IM were investigated using price drivers from the German intraday market [13] and [12], but as [11] and [14] show, the Nordic market in its current maturity is less predictable. To model continously updated information, we apply a rolling horizon approach, as done by [8], [9] and [10] in similar energy applications.

## II. MARKET MODELLING

Post-spot bidding is possible for each hour after IM opens. The uncertainties in demand, load and prices are assumed to decrease when the bid hour is closer to the production hour. An overview of the time horizon of the post-spot bidding problem can be seen in Fig. 1. Intraday bidding starts at 14:00 the day before production and IM-bids can be submitted up to one hour prior to production, whereas BM-bids can be submitted up to 45 minutes before production. This results in 33 hours of post-spot bidding. It is assumed that IM-bidding is completed prior to BM-bidding.

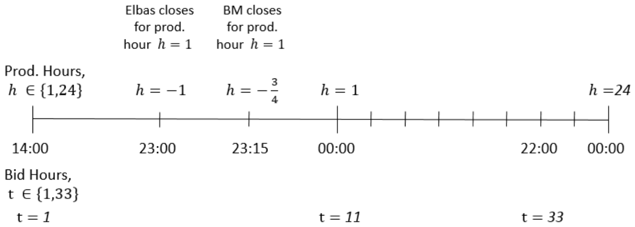

Fig. 1. Time line of the bidding problem.

IM is modelled based on historical order book data. The residual demand curves are linearised in order to create a tractable problem. The intraday demand was categorised into 3 different states (low, medium, high), and to describe the relationship between bid volume and bid premium, linear residual demand curves were fitted to the historical intraday order depth. Each demand scenario has an associated linear regression curve, and the total number of IM-scenarios is generated by adding stochastic residuals to the linear regression curves. Every scenario has an associated scenario probability. Because the premium described by the demand curves is a function of a given volume, the objective function becomes non-linear. To obtain a linear model, the demand curves are therefore linearised by dividing the demand into volume segments. The size of the volume segments is the upper bound of the volume that can be bid within that segment. Each combination of volume segment and demand scenario (block) is assigned an acceptance share, which is defined as the historical probability that a bid within that block is accepted.

BM-premiums are forecasted using time series models and Markov states to define the regulating state. Based on the work of [15], auto regressive moving average (ARMA) models are fitted to forecast upward (BM$\uparrow$) and downward (BM$\downarrow$) regulated premiums, whereas the regulation state is defined based on transition probabilities. Missing values in the input data are handled according to [16]. Based on the correlation

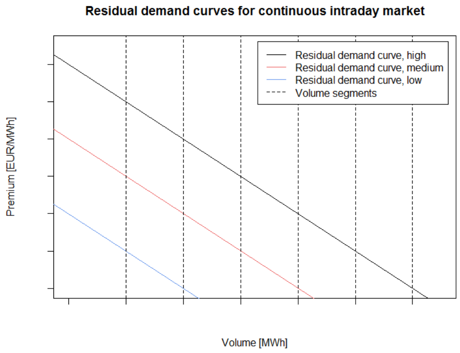

Fig. 2. Theoretical residual demand curves for continuous intraday trading with discretised volume segments.

presented in Table I, the BM-premiums and BM-volumes are considered independent of each other except for the balancing state, and the BM-volumes are therefore forecasted using generalised extreme value (GEV) distributions similar to [17].

TABLE I
CORRELATION STUDY OF THE INTRADAY MARKET AND THE BALANCING MARKET, 2015 - 2016

|  | BM-pre. /BM-vol. | BM↑-pre. /IM-pre. | BM↓-pre. /IM-pre. | BM↑-vol. /IM-vol. | BM↓-vol. /IM-vol. |
|---|---|---|---|---|---|
| Corr. | 0.49 | 0.36 | -0.40 | 0.14 | -0.02 |

The empirical correlation between IM and BM is presented in Table I. The correlation is based on Nord Pool data from 2015 - 2016 [18]. Although there is a correlation between the BM and IM premium, they are treated as independent variables in this study.

## III. MATHEMATICAL MODEL

The mathematical model is a multistage SMIP where the stochastic scenarios represent different realizations of intraday demand, balancing market prices and production. The first stage decision is to decide the intraday bid volume based on a scenario dependent IM-price. Then, the acceptance shares of the different bid segments are revealed, and the IM-volume sold or bought is decided based on the bid volume in each segment and their associated acceptance shares. The total accepted bid volume for each scenario is thus the second stage decision by simple recourse. After the IM-volumes are decided, the producer has the possibility to bid in the balancing market. This makes the balancing market volume the third stage decision. The bid volume depends on an uncertain balancing market price. After all commitments are settled the total production is decided. For every bid hour, the scenario structure is repeated. To handle the updated information when bidding closer to the hour of operation, the problem is formulated using a rolling horizon approach.

Table II defines the sets and their corresponding indices, whereas the decision variables are presented in Table III.

TABLE II
SETS AND INDICES IN THE OPTIMISATION MODEL.

| **Set** | Index | Explanation |
|---|---|---|
| $\mathcal{S} = \{1,...,S\}$ | $s \in \mathcal{S}$ | Set of scenarios $s$ |
| $\mathcal{H} = \{1,...,H\}$ | $h \in \mathcal{H}$ | Set of production hours $h$ |
| $\mathcal{H}^b = \{1,...,H^b\}$ | $h \in \mathcal{H}^b$ | Set of bid hours $h$ |
| $\mathcal{I} = \{1,...,I\}$ | $i \in \mathcal{I}$ | Set of generators $i$ |
| $\mathcal{J} = \{1,...,J\}$ | $j \in \mathcal{J}$ | Set of reservoirs $j$ |
| $\mathcal{F} = \{1,...,F\}$ | $f \in \mathcal{F}$ | Set of production segments $f$ |
| $\mathcal{K} = \{1,...,K\}$ | $k \in \mathcal{K}$ | Set of IM demand curve segments $k$ |

TABLE III
DECISION VARIABLES IN THE OPTIMISATION MODEL.

| **Variable** | Explanation |
|---|---|
| $c_{shi}$ | Induced start-up cost for generator $i$ in hour $h$ for scenario $s$ |
| $d_{shi}$ | Discharge by generator $i$ for scenario $s$ |
| $q_{shi}$ | Net production for generator $i$ in hour $h$ for scenario $s$ |
| $s_{shj}$ | Spill from reservoir $j$ in hour $h$ for scenario $s$ |
| $u_{shi}$ | 1 if generator $i$ is committed in hour $h$ for scenario $s$, 0 else |
| $v_{shj}$ | Reservoir volume in reservoir $j$ in hour $h$ for scenario $s$ |
| $x_{sh}^{BM}$ | Volume committed to BM in hour $h$ for scenario $s$ |
| $x_{shk}^{E}$ | Volume bid to IM in segment $k$ in hour $h$ for scenario $s$ |

The deterministic equivalent of the objective function of the SMIP given by (1) maximizes profit for all scenarios $s \in \mathcal{S}$ and production hours $h \in H$. The intraday income is given by the IM-price, $\rho^E_{shk}$, and the volume sold, $\sum_{k\in\mathcal{K}} \Pi_{sk} x^E_{shk}$, for the volume bid in each segment $k \in \mathcal{K}$. Here, $\Pi_{sk}$ is the acceptance share. The acceptance share decreases with increasing bid premium and volume. In the balancing market, the profit is given by the BM-price, $\rho^{BM}_{sh}$, and the volume, $x^{BM}_{sh}$. The production costs are given by the alternative cost of using water, which is decided by the product of the constant water value, $W^0_j$, the change in reservoir level and the induced start-up cost, $c_{shi}$. Because the total use of water for a production hour is included in the objective, the day-ahead profit must also be included as a parameter.

$$\begin{aligned} \max \sum_{s\in\mathcal{S}} Pr_s \Big[ \sum_{h\in\mathcal{H}} \Big( \sum_{k\in\mathcal{K}} \Pi_{sk}\rho^E_{shk}x^E_{shk} + \rho^{BM}_{sh}x^{BM}_{sh} \Big) \\ - \sum_{j\in\mathcal{J}} W^0_j \eta_j \Big( \sum_{h\in\mathcal{H}\setminus 1} (v_{s(h-1)j} - v_{shj}) + V^0_{sj} - v_{s1j} \Big) \\ - \sum_{h\in\mathcal{H}} \sum_{i\in\mathcal{I}} c_{shi} \Big] + \sum_{h\in\mathcal{H}} P^{Spot}_h X_h \quad (1) \end{aligned}$$

The necessary constraints are given as follows:

$$|x^E_{shk}| \le |E^E_k|, \ \ s \in \mathcal{S}, h \in \mathcal{H}, k \in \mathcal{K} \quad (2)$$

$$|x^{BM}_{sh}| \le |E^{BM}_{sh}|, \ \ s \in \mathcal{S}, h \in \mathcal{H} \quad (3)$$

$$\sum_{k\in\mathcal{K}} \Pi_{sk}x^E_{shk} + X^E_{sh} + x^{BM}_{sh} + X_h = \sum_{i\in\mathcal{I}} q_{shi}, \quad s \in \mathcal{S}, h \in \mathcal{H} \quad (4)$$

$$\sum_{k\in\mathcal{K}} x^{E}_{shk} + X^{E}_{sh} + x^{BM}_{sh} + X_h \le \sum_{i\in\mathcal{I}} Q^{max}_{i}, \quad s\in\mathcal{S}, h\in\mathcal{H} \tag{5}$$

$$q_{shi} \le Q^{max}_{i} u_{shi}, \;\; s\in\mathcal{S}, h\in\mathcal{H}, i\in\mathcal{I} \tag{6}$$

$$q_{shi} \ge Q^{min}_{i} u_{shi}, \;\; s\in\mathcal{S}, h\in\mathcal{H}, i\in\mathcal{I} \tag{7}$$

$$v_{shj} - v_{s(h-1)j} = I_{hj} - \sum_{i\in\mathcal{I}} \Gamma_{ij} d_{shi} + \sum_{j'\in\mathcal{J}} \Lambda_{jj'} s_{shj'}, \quad s\in\mathcal{S}, h\in\mathcal{H}\backslash 1, j\in\mathcal{J} \tag{8}$$

$$v_{s1j} - V^{0}_{sj} = I_{1j} - \sum_{i\in\mathcal{I}} \Gamma_{ij} d_{s1i} + \sum_{j'\in\mathcal{J}} \Lambda_{jj'} s_{s1j'}, \quad s\in\mathcal{S}, j\in\mathcal{J} \tag{9}$$

$$q_{shi} \le A_{if} u_{shi} + B_{if} d_{shi}, \quad s\in\mathcal{S}, h\in\mathcal{H}, i\in\mathcal{I}, f\in\mathcal{F} \tag{10}$$

$$d_{shi} \le D_i u_{shi}, \;\; s\in\mathcal{S}, h\in\mathcal{H}, i\in\mathcal{I} \tag{11}$$

$$c_{shi} \ge C_i(u_{shi} - \max[u_{s(h-1)i},\, U^{0}_{hi}]), \quad s\in\mathcal{S}, h\in\mathcal{H}, i\in\mathcal{I} \tag{12}$$

$$c_{s1i} \ge C_i(u_{s1i} - U^{0}_{1i}), \;\; s\in\mathcal{S}, i\in\mathcal{I} \tag{13}$$

$$\omega_{sh} = \omega_{\zeta h}, \;\; s\in\mathcal{S}_{\zeta}, h\in\mathcal{H}_{\zeta}, \zeta\in\mathcal{Z} \tag{14}$$

Constraint (2) and (3) limit the volumes bid in the markets. The upper intraday demand volume that can be bid within each segment is $E^{E}_{k}$, while the BM-volume is limited by a stochastic volume for each production hour, $E^{BM}_{sh}$.

The delivered obligations committed in the different markets must be covered by the net production, $q_{shi}$, and is taken care of in (4). The constraint includes the IM-volumes sold or bought in previous bid hours to be delivered in the given production hour, $X^{E}_{sh}$. For buy volumes it is possible to reduce production as long as delivered obligations are fulfilled. Because only a percentage of volumes bid to IM is answered due to the low liquidity described by the acceptance share, (5) is necessary to make sure that the volume bid to IM does not exceed the total maximum production limitations, $\sum_{i\in\mathcal{I}} Q^{max}_{i}$.

The net production cannot exceed the generator's capacity limits, namely maximum production, $Q^{max}_{i}$, and minimum production, $Q^{min}_{i}$, given by (6) and (7).

Change in reservoir level determines the alternative cost of using water and is described by (8). For the initial hour, (9) is used where $V^{0}_{sj}$ is the initial volume in the reservoir. The reservoir volume, $v_{shj}$, increases with inflow, $I_{hj}$, and the decrease is determined by the discharge, $d_{shi}$, and spill, $s_{shi}$. For cascaded reservoirs, the discharge and spill for upstream reservoirs affect the reservoirs downstream. $\Gamma_{ij}$ explains the connection between reservoir $j\in\mathcal{J}$ and generator $i\in\mathcal{I}$. $\Lambda_{jj'}$ explains the connection between two reservoirs, $j$ and $j'$.

Generator bounds are obtained by (10) and (11). Production is limited by a linearisation of the convex cost function describing the correlation between production and discharge (P-Q curve), with $A_{if}$ as the intercept and $B_{if}$ as the slope of the function. Maximum discharge for each generator is given by $D_i$.

**Algorithm 1:** Complete rolling horizon model

```
for $h \in \mathcal{H}$ do
    Generate residual demand curves and associated acceptance shares
    for IM-scenarios
end for
for $b \in \mathcal{H}^b$ do
    Generate BM-scenarios for BM-premiums and draw BM-volume
    bounds
    Merge IM- and BM-scenarios into one scenario tree
    for $h \in \mathcal{H}$ do
        Update dynamic input files (BM-scenarios, initial reservoir,
        generator status, total IM-volumes)
        if $|\mathcal{H}| < 24$ then
            Update time horizon of IM-scenarios
            Update all input files to match time horizon
        end if
        Run optimisation model/solve SMIP
        Update BM-premium and IM bid volumes
    end for
end for
```

Start-up costs affect the profit and are modelled in (12) and (13), which consider the initial hour. If the generator start-up from one hour to the next, $c_{shi}$, is assigned the start-up cost, $C_i$. Since the generator may be running already due to spot commitments, the original generator state in hour $h\in\mathcal{H}$ is indicated by $U^{0}_{hi}$.

Constraint (14) describes the non-anticipativity constraint which links the equal stage decisions together and makes sure that all decisions made at later stages are based on the same information.

## *A. Rolling horizon approach*

Due to the lag in price discovery, where the realised BM-prices are not known before the hour after operation, there will never be perfect information about the balancing market at the time of bidding in the post-spot markets. The closer the hour of operation, the less uncertain the forecasted BM-scenarios are. Thus, the optimisation model is formulated using an internal rolling horizon approach, which for each bid-hour takes into account the updated BM forecast from the previous bid-hours. The purpose of this is to obtain a realistic model where the participants continuously bid in IM throughout the day and have to take earlier traded volumes and updated BM-forecasts into account. The producer is assumed regulated according to the BM-bid the hour before operation, and the model considers the BM-forecasts when placing IM-bids for future bid hours. The IM-scenarios are considered independent of bid hour, and are therefore generated for the entire problem horizon. Dynamic parameters that are affected by the previous bid hours, like BM-forecast, initial reservoir level, generator status and total intraday commitments, must however be updated during the rolling horizon in order to keep the model as accurate as possible. A total overview of the procedure used to run the rolling horizon multistage SMIP is presented in Algorithm 1. For each bid hour, the multistage SMIP is solved for the remaining production hours.

## IV. CASE STUDY AND RESULTS

The outlined framework was tested on a Norwegian hydro power producer located in Nord Pool's bidding area NO2. The first Wednesday in every month of 2016 is modelled to capture seasonal differences described by input parameters as day-ahead commitments, inflow, initial reservoir level and water values.

An important feature of a stochastic programming problem is the stability of the scenario tree.The preferable scenario tree is small and still satisfies stability measures. In-sample and out-of-sample stability testing as presented by [19] have been performed for a varying number of IM- and BM-scenarios. The tests show that the number of IM-scenarios have small impact on the total stability, and the scenario tree is concluded stable for 10 IM-scenarios and 30 BM-scenarios. This yields a total of 300 scenarios for each bid hour.

Properties of the generated scenarios are presented in Table IV. It can be seen that the IM-price normally is more profitable than the BM-price for both buy and sell volumes. This indicates that intraday participants are willing to accept higher bid premiums, compared to the generally low BM-premiums. The optimization problem of the power producer is however not only about where the premiums are higher, the probability of being dispatched in both markets must also be assessed. In this case, the probability of regulation in the balancing market is much higher than the intraday acceptance shares.

To measure the value of intraday trading the problem is solved with the intraday trade volume fixed to zero. The results can be seen in Table V. There is a marginal increase of profit when including the possibility of intraday trading, with the average value for all case dates quantified as 0.180 % or 115.3 €. For a hydro power producer with an income in the size of several thousand Euros a day, the contribution from intraday trading is small. Considering that bids are submitted for almost every scenario, the low market liquidity is reflected by the small added value of intraday trading.

Table V shows that the days in April, July, August and September where only buy volumes are traded have a lower average value of intraday trading. The average gain for these days is only 0.130 %, compared to the day in October with only sell bids which has a gain of 0.410 %. This indicates that it is more profitable to sell additional volumes in IM than to buy IM-volumes to restrain production.

The increased value from intraday trading is however low due to the low market liquidity where few bids are accepted. To perform a theoretical study which shows how the value of intraday trading can develop with increased market liquidity, or increased acceptance shares in this case, a future IM with fictive liquidity is implemented. The acceptance shares $\Pi_{sk}^{Sell}$ and $\Pi_{sk}^{Buy}$ are increased to simulate a market with higher demand and more participants. One date from each season of the year is presented. The results of multiplying the acceptance shares with a factor of 10 and 50 are shown in Table VI. All other parameters are kept equal to the present model. The scaling factors are chosen relatively high based on the originally low acceptance shares.

Table VI shows that the value of including intraday trading will increase with a more liquid IM. Since the value of intraday trading is limited by the possibility to sell or buy volumes, it is reasonable that the gain is not proportional to the scaling factors. Larger scaling factors give the opportunity to buy or sell larger volumes, but the option to produce more can be limiting.

From the case study three main factors that influences the value of the intraday market have been identified:

- The producer's position in the market merit-order supply curve
- The flexibility of the production capacity
- The liquidity of the intraday market

The days with water value close to spot price are the ones that yield the highest profit from including intraday trading. The interpretation is quite straightforward: If the market price is much higher than the marginal cost (in our case: the water value), it would normally be fully committed in the day-ahead market. Likewise, if the market price is far lower than the operating cost of the plant, it will not be committed in the day-ahead market, and the volumes and premiums in the intraday market are barely enough to grant a start-up. However, when the water value is close to the spot price, the plant is likely to run on the point of best efficiency in the day-ahead market, with flexibility to ramp both up and down. The cost of doing so will not be too far away from the spot price, and thus a profit can be earned even with moderate IM premiums.

Days with only intraday buys gives less value from the intraday market than in days with both buy and sales. This is related to both the shape of the supply curve and the IM premiums: If the market supply curve is convex, the premiums for increasing production should be higher than for reducing production with the same amount. Also for hydro power plant, running below the point of best efficiency will increase production costs, and therefore buying power back does not necessarily reduce production costs proportionally.

The more the degrees of freedom in determining production, the higher the possibilities are for making profit in the IM. Factors that typically increase production flexibility give higher value - such as high reservoir filling in the storage reservoirs or free spinning capacity of the generators after the commitment in the day-ahead market. Large inflow on the other hand, often reduces flexibility, since it becomes necessary to run the plant in a certain manner to avoid spillage.

## V. CONCLUSION

Modelling IM with stochastic residual demand curves gives a more accurate presentation of the market by revealing the actual demand and not only describing realised trades. An advantage of the model presented in this paper is that it makes it possible to quantify the value of participating in IM for a hydro power producer. An internal rolling horizon gives a real world approach by describing how the post-spot

TABLE IV

PERCENTAGE OCCURRENCE FOR FEATURES OF POST-SPOT TRADING: RELATIONSHIP BETWEEN INTRADAY BID TYPES AND POST-SPOT PRICES.

| Date | 06/01 | 03/02 | 02/03 | 06/04 | 04/05 | 01/06 | 06/07 | 03/08 | 07/09 | 05/10 | 02/11 | 07/12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| % IM sell bids | 59.26 | 11.67 | 60.93 | 0 | 13.70 | 81.30 | 0 | 0 | 0 | 100 | 63.52 | 99.07 |
| % IM buy bids | 41.30 | 87.41 | 85.25 | 100 | 86.30 | 17.79 | 100 | 100 | 100 | 0 | 36.48 | 0.74 |
| % IM sell $>$ BM | 80.00 | 89.75 | 86.19 | 85.85 | 86.19 | 89.50 | 84.06 | 85.85 | 86.53 | 87.77 | 86.80 | 87.81 |
| % IM buy $<$ BM | 95.48 | 98.10 | 96.27 | 97.12 | 96.54 | 97.38 | 97.21 | 97.12 | 96.73 | 96.46 | 95.84 | 96.85 |

TABLE V

OBJECTIVE VALUE FOR THE FIRST BID HOUR IN THE ANALYSIS. INCREASE IN PROFIT FROM INTRADAY TRADING.

| Date | 06/01 | 03/02 | 02/03 | 06/04 | 04/05 | 01/06 | 06/07 | 03/08 | 07/09 | 05/10 | 02/11 | 07/12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spot+BM [€] | 75,221 | 49,846 | 59,268 | 71,293 | 82,057 | 89,022 | 65,372 | 78,421 | 67,828 | 25,240 | 65,873 | 143,652 |
| Spot+BM+IM [€] | 75,383 | 49,970 | 59,366 | 71,311 | 82,181 | 89,118 | 65,472 | 78,519 | 67,974 | 25,344 | 66,021 | 143,819 |
| $\Delta$ [€] | 162.0 | 123.3 | 97.6 | 18.5 | 124 | 96.2 | 99.8 | 98.6 | 145.5 | 103.6 | 147.9 | 167 |
| $\Delta$ [%] | 0.215 | 0.247 | 0.165 | 0.026 | 0.151 | 0.108 | 0.153 | 0.126 | 0.215 | 0.410 | 0.225 | 0.116 |

TABLE VI

OBJECTIVE VALUE AND THE PERCENTAGE VALUE OF INTRADAY FOR TWO INCREASED LIQUIDITY SCENARIOS.

| Date | 03/02 | 04/05 | 03/08 | 07/12 |
|---|---|---|---|---|
| Spot+BM [€] | 49,846 | 82,057 | 78,421 | 143,652 |
| Incl. IM [€] 10*$\Pi_{sk}$ | 51,137 | 83,016 | 79,197 | 144,994 |
| Incl. IM [€] 50*$\Pi_{sk}$ | 54,120 | 86,253 | 81,693 | 150,226 |
| $\Delta$ [%] 10*$\Pi_{sk}$ | 2.588 | 1.168 | 0.990 | 0.934 |
| $\Delta$ [%] 50*$\Pi_{sk}$ | 8.573 | 5.114 | 4.172 | 4.576 |

markets' uncertainties develop while taking into account the bids committed in the previous bid hours.

Applying the model framework to a realistic case study shows that the value of intraday trading is higher when the water value is close to the spot price, and when there is production flexibility through available generator capacity and water in the reservoirs. The gain is larger when selling in IM than buying from IM in order to reduce own production. Due to the low market liquidity, the value of intraday trading is low compared to the overall profit of a hydro power producer.

## ACKNOWLEDGMENT

Financial support from The Research Council of Norway, project number 245284/E20 is greatly appreciated.

## REFERENCES

[1] C. Weber, *Adequate intraday market design to enable the integration of wind energy into the European power systems*, Energy Policy, 38(7):3155-3163, 2010.

[2] A. Ugedo, E. Lobato, A. Franco, L. Rouco, J. Fernandez-Caro and J. Chofre, *Strategic bidding in sequential electricity markets*, IEE Proceedings - Generation, Transmission and Distribution, 153(4):431-442, 2006

[3] S.-E Fleten and T. K. Kristoffersen, *Stochastic programming for optimizing bidding strategies of a nordic hydropower producer*, European Journal of Operational Research, (181):916-928, 2007.

[4] S.-E. Fleten, D. Haugstveit, J.-A. Steinsb, M. Belsnes and F. Fleischmann, *Bidding hydropower generation: Integrating short- and long-term scheduling*, Proceeding - 17th Power Systems Computations Conference PSCC: 352-358, 2011.

[5] E. K. Aasgard, G. S. Andersen, and S.-E Fleten and D. Haugstvedt, *Evaluating a stochastic-programming-based bidding model for a multireservoir system.*, IEEE Transaction on Power Systems, 29(4):1748-1757, 2014.

[6] E. Faria and S.-E. Fleten, *Day-ahead market bidding for a Nordic hydropower producer: taking the Elbas market into account*, Computational Management Science, 8(1-2):75101, 2011.

[7] T.K. Boomsma, N. Juul and S.-E. Fleten, *Bidding in sequential electricity markets: The Nordic case*, European Journal of Operational Research, 283(3):797-809, 2014.

[8] P. Beraldi, A. Violi, N. Scordino, and N. Sorrentino, *Short-term electricity procurement: A rolling horizon stochastic programming approach*, Applied Mathematical Modelling, 35(8):3980-3990, 2011.

[9] M. T. Devine, S. A. Gabriel and S. Moryadee, *A rolling horizon approach for stochastic mixed complementarity problems with endogenous learning: Application to natural gas markets*, Computers & Operations Research, 68:1-15, 2016.

[10] B. R. Champion and S. A. Gabriel, *A multistage stochastic energy model with endogenous probabilities and a rolling horizon*, Energy and Buildings, 135:338-349, 2017.

[11] R. Scharff and M. Amelin, *Trading behaviour on the continuous intraday market Elbas*, Energy Policy, 88:544:557, 2016.

[12] E. Garnier, and R. Madlener, *Balancing forecast errors in continuous-trade intraday markets*, Energy Systems, 6(3):361, 2015.

[13] R. Kiesel and F. Paraschiv, *Econometric analysis of 15-minute intraday electricity prices*, Energy Economics, 64:77-90, 2017.

[14] E. Engmark and H. Sandven, *Optimal post-spot bidding for a wind power producer in the Nordic power market*, unpublished, project report in course TIø4500 at Norwegian University of Science and Technology, 2016.

[15] M. Olsson and L. Soder, *Modeling Real-Time Balancing Power Market Prices Using Combined SARIMA and Markov Processes*, IEEE Transactions on Power Systems, 23(2):443-450, 2008.

[16] E. Erdogan, M. Sheng, A. Beygelzimer and I. Rish, *Statistical models for unequally spaced time series*, proceedings of the 2005 SIAM International conference on data mining, 626-630, 2005.

[17] S. Jaehnert, H. Fahramand and L. G. Doorman, *Modelling of prices using the volume in the norwegian regulating power market*, PowerTech, 2009 IEEE Bucharest, 2009.

[18] NordPool. *Historical Market Data* [Online] Availble: http://www.nordpoolspot.com/historical-market-data/

[19] M. Kaut and S. W. Wallace, *Evaluation of Scenario-Generation Methods for Stochastic Programming*, Pacific Journal of Optimization, 3(2):257271, 2007.