Value of Multi-Market Trading for a Hydropower Producer

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***Abstract*—We present a case study for a price-taking hydropower producer trading in the three short-term energy markets, day-ahead, intra-day and the balancing market. The study uses a scheduling software with a detailed representation of a real Norwegian power plant optimizing the operations and trade for historical market data from 2015. The motivation for the study is to make an assessment of the value of trading in multiple markets relative to day-ahead trading only, utilizing a simplifying perfect foresight assumption. This gives the basis for assessing the value of developing more complex models with a more precise representation of uncertainty in the decision process. The analysis show a significant added value from participating in more markets than day-ahead, with the balancing market giving the largest contribution.**

I. Introduction

The Nordic power system has a large share of hydropower. In Norway, the share of hydropower production was over 95% in 2016, while for the other Nordic countries there is a mixture of thermal power, nuclear and hydropower. Currently, the day-ahead market is by far the largest market for trading power in the Nordic system. However, due to increasing variability in power production from renewables and increased capacity for power transmission to other European markets, the importance and liquidity of short-term markets are expected to increase. In this paper, we analyse the extent that hydropower producers can achieve added profits through participation in multiple markets (multi-market). We compare the achieved profits from multi-market participation with participation only in the day-ahead market assuming coordinated trades. Coordinated trades in this context refers to the producer taking all available markets into account when deciding on trade in each of the markets. In the alternative, sequential trading, the trades in the markets is decided market-by-market. This means that the producer decides on the market trade as if the current market is the last. The main motivation for the analysis is to assess the usefulness of extending and revising existing bidding and scheduling tools and procedures to capture the multi-market situation. Additionally, we will identify the main value-drivers for multi-market trading.

The Nordic electricity market has the same main structure as in EntsoE's network codes with markets trading energy and ancillary services[1], [2]. This study focus on the energy trades including day-ahead (DA), intra-day (ID) and balancing market (BM), following the Nordic market rules.

The literature on multi-market analysis has grown substantially over the last years. Due to the particular energy mix in the Nordic region and slight differences in market rules in different regions, we focus on literature analysing multi-market trade in the Nordic market. Most commonly, the analyses are conducted within a stochastic programming framework. [3] present a case study for trading in the day-ahead and intra-day markets, and find the added value of coordinated bidding to be less than 0.65% compared to sequential bidding. Multiple papers have looked into the coordinated bidding in the day-ahead and balancing markets. [4] observe a value of less than 0.1% for coordinated bidding relative to sequential bidding, while [5] find values up to 1.1% of coordinated trade relative to only day-ahead trade. [6] reports values of coordinated bidding relative to sequential bidding ranging from 4%-25% depending on the time of year and the size of the deviation between price expectation in the two markets. This paper will add to the literature by presenting a study where trades in all three energy markets in the Nordic power market, DA, ID and BM, are evaluated together.

II. Model and test setup

In our study, we use a deterministic model with one year horizon and hourly resolution. Providing perfect foresight through a deterministic model is an ideal state that do not capture the real uncertainties seen by the market participants, but allows us to calculate upper bounds on the real values with substantially less complexity than using a full-scale three-market stochastic model. This approach is based on the same principle of perfect foresight used by [6] when establishing an upper bound for coordinated bidding. Such bounds forms a basis for assessing the potential value of developing more complex models.

We take the perspective of a risk-neutral price-taking hydropower producer. The producer's decision problem is modeled in the short-term hydropower scheduling software SHOP [7], which is used for bidding and short-term scheduling by a range of hydropower producers. The underlying optimization model has a detailed representation of the production system, including amongst other cascades of reservoirs, production functions with head effects and binary start and stop decisions

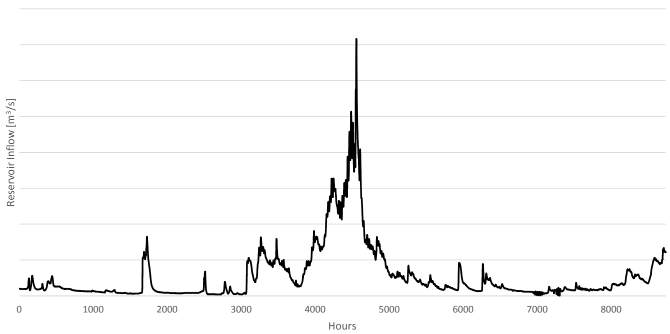

Fig. 1. Inflow profile for the two reservoirs based on observations from 2015.

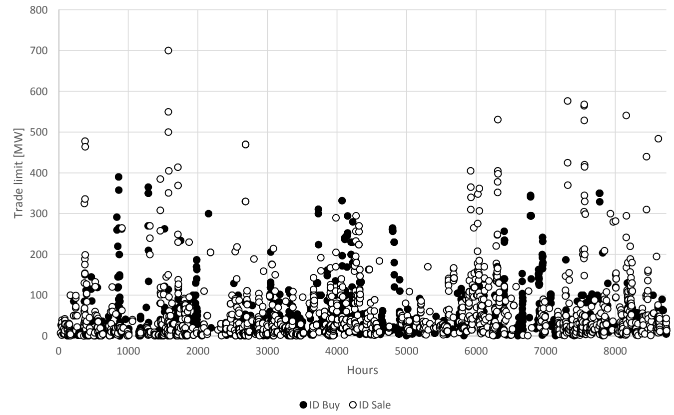

Fig. 2. Trade limits for purchase and sale in ID given by sum of observed trades in 2015.

for individual generators. The software uses successive linear programming, iteratively solving mixed-integer programs and linear programs, to solve the underlying non-convex optimization problem [8].

A. Power plant description

The test case used in our paper consists of real data from 2015 for a Norwegian power plant with two reservoirs in a cascade and two parallel generators. Total installed capacity is 620 MW. Generator utilization[1] over an average year is 33%. In line with the perfect foresight assumption the modelled inflow is deterministic, representing the historical inflow in 2015, which gave a degree of regulation[2] of 0.46. The reservoirs are closely located and are modelled with the same historical inflow profile provided by the national water resource authority [3], which is given in Figure 1. The initial reservoir levels were set according to the average filling level in the plant's price area in the start of 2015. The piecewise linear water value function, representing the marginal value of water at the end of the model horizon, was scaled to give a end reservoir level that corresponded to the average filling level in the price are in the end of 2015.

B. Market description

The market data are those observed in the Norwegian price area NO5 in 2015. Three markets are included in the analysis: day-ahead (DA), intraday (ID) and the balancing market (BM). All these markets have electric energy as the traded product, and they close in the order they are listed here. The two first markets are operated by NordPool, while BM is operated by the TSO Statnett. We assume that the producer is a price taker in all markets in our analysis. The traded volumes in ID and BM is relatively small compared to, both, the volumes traded in DA and to the modelled production capacity. Therefore, the purchase and sale positions that can be taken in these markets are constrained in our analysis, representing the estimated market depth for the given price in each market.

DA has an hourly price set by a market clearing. BM is a tertiary reserve energy market where the participants offer capacity and are renumerated according to the energy quantity activated (used) by the TSO real time. There are separate up- and downregulation prices which are set hourly. The upregulation price is per design higher than the DA price and vice versa for downregulation. Upregulation corresponds to sales, and downregulation to purchase for a producer. The historically activated quantity for each hour is used as the trade limits in our analysis. In some hours, both up- and downregulation is activated. This happened in 72 hours in 2015. It should be noted that our work does not include the modelling of any bidding in DA or BM, but rather collapses the bidding and clearing process in an optimization of the quantities traded in each market.

ID has continuous trading with pay-as-bid pricing. This means, as opposed to the two other markets, ID does not have a cleared market price, but one price for each settled trade. In the modelling this is approximated with two prices, one for sale and one for purchase, in each hour. The sales price in an hour is calculated from the historically settled trades (ticker data) as the volume weighted average price of all trades for delivery in that hour where the seller was located in NO5. The same procedure has been used for calculating the purchase price. The sum of the volumes in these trades are defined as the sales and purchase trade limits, respectively.

Figure 2 and Figure 3 show the trade limits for ID and BM, respectively. To make the plots more readable zero-values are left out. The plots show that the traded volumes are larger i BM than in ID, both in terms of number of traded hours and quantity traded[4]. The production capacity in the modelled powerplant exceeds the sales limits in almost all hours, which confirms the need for limits on sale in this study.

Table I gives an aggregated view of the input prices. As can be observed, both ID and BM have, on average, higher sales price and lower purchase price than DA. All market prices are highly volatile, as indicated by the standard deviations. The prices in the three markets are strongly correlated, as can be seen in Table II.

[1]Annual production [MWh] / Installed capacity [MW] / 8760 [h per year]
[2]Total reservoir volume [Mm^3] / Annual inflow [Mm^3]
[3]The Norwegian Water Resources and Energy Directorate

[4]Note the different scale in the y-axis.

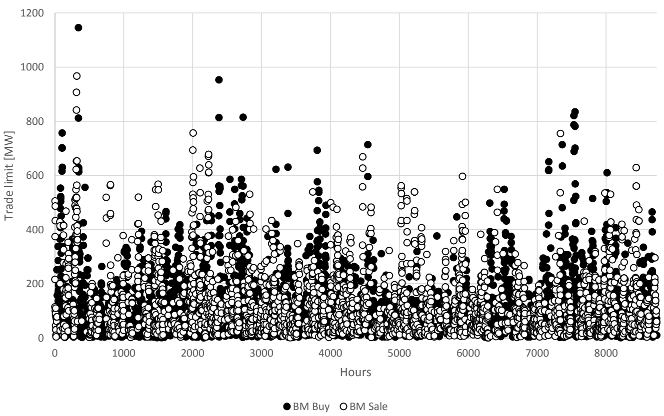

Fig. 3. Trade limits for purchase and sale in BM given by actual activated quantities in 2015.

TABLE I
CHARACTERISTICS OF PRICE INPUT IN €. THE LAST ROW, 'AVAILABLE', CONTAINS THE PERCENTAGE OF HOURS WITH A TRADE LIMIT LARGER THAN ZERO.

	DA	ID buy	ID sale	BM buy	BM sale
Mean	19.80	19.68	21.05	15.14	24.07
Std.dev.	7.62	8.33	7.49	7.32	9.18
Available	100 %	18 %	22 %	35%	30 %

C. Test setup

We run the model with a set of different assumptions that can be organized in two dimensions, *Markets* and *Trade modes*. *Markets* describes which markets are included in the analysis. The combination of markets that we have included in our analysis is listed in Table III. *Trade modes* describe different assumptions on market behavior, and the different variations used in our analysis are shown in Table IV. Since we only have access to actual trades, and not all bids in the market, we have to estimate the trade limits for each market. We have chosen to use two levels for trade limits, allowing unlimited trades and limiting trades with actual traded volumes. All combinations of the two dimensions are optimized, which gives 16 model runs.

III. RESULTS AND DISCUSSION

In the following, we present the results from our analysis. We focus on the added value of trading in multiple markets, first with sale only and later with both purchase and sale. Figure 4 shows the difference in achieved profit by selling in multiple markets relative to selling in DA only. As we can see from the figure, the largest increase in profits is from trading in all three markets. The added value from including ID in addition to DA and BM is small. For all these runs, it is only possible to sell power in the markets (such that pure financial arbitrage is not possible). Due to this restriction, the value we see from including new markets is due to the availability of higher prices in some hours in ID, BM or both. Within the market limits and production system limits the model will choose to sell in the markets and hours with the highest prices. The difference between the grey and the white bar in Figure 4 is due to assumptions on the liquidity of the added markets. In the white column, the sale volumes in the ID and BM markets are constrained to historically observed trades, while in the grey column the sale volumes are only limited by the physical production system. As is evident from the figure, the strictest liquidity assumptions has a large impact on the value of multi-market trade. While *Unlimited sale* corresponds to the theoretical perfect competition assumption, even the *Limited sale* is an optimistic estimate since we assume that the single producer in our analysis is the only participant in the markets.

In the next set of analysis, we include the possibility for the producer to also purchase power in the markets. There are several motivations for a producer to buy power in one or more markets. The traditional motivation is to adjust the accumulated market obligation from closed trades to an efficient production level. The need to adjust the loads committed in DA can be due to both uncertainty revealed after the DA market was closed and deviations between the piecewise linear DA bidding curve and the underlying marginal cost curve. Since neither uncertainty nor bidding is included in our modeling, this value from short-term market trades is not captured in our analysis. Another motivation for purchasing power is to enhance the value of storage capacity by buying energy whenever a market purchase price is below the expected marginal cost of production. To realize this value a pumping facility, to enable negative net market positions,

TABLE II
CORRELATIONS BETWEEN SALES PRICES AND PURCHASE PRICES IN DIFFERENT MARKETS.

	Buy			Sale		
	DA	ID	BM	DA	ID	BM
DA	1.00	0.95	0.93	1.00	0.80	0.94
ID	0.95	1.00	0.90	0.80	1.00	0.79
BM	0.93	0.90	1.00	0.94	0.79	1.00

TABLE III
VALUES IN THE ANALYSIS DIMENSION *Market*.

Market name and order
DA
DA+ID
DA+BM
DA+ID+BM

TABLE IV
VALUES IN THE ANALYSIS DIMENSION *Trade modes*.

Name	Description
Pure market trade	No production capacity is available, only market trades within the trade limits to exploit arbitrage within the hour.
Unlimited sale	No limit on sale in any market, zero purchase in all markets.
Limited sale	As 'Unlimited sale', but sale limits added for ID and BM.
Limited sale & buy	As 'Limited sale', but with limited purchase possible in ID and BM and unlimited purchase possible in DA.

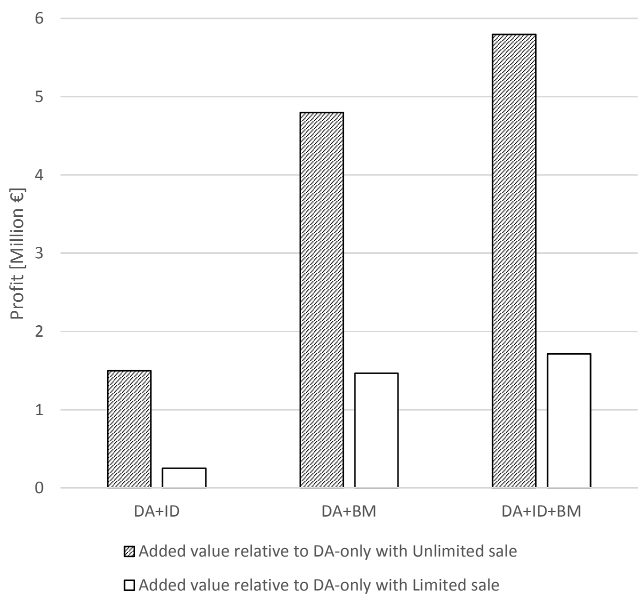

Fig. 4. Added value of coordinated sale in multiple markets relative to DA sale only

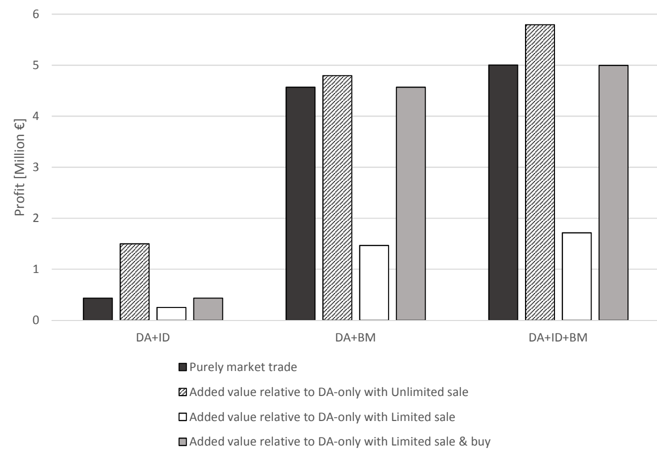

Fig. 5. Added value of coordinated purchase and sale in multiple markets relative to DA trade only

is needed. Finally, the possibility to purchase power allows the producer to do market speculation, and, given our perfect foresight assumption, exploit arbitrage possibilities in the markets. Without a storage, only within-hour arbitrage would be possible, while a reservoir enables inter-hour arbitrage.

While Figure 4 shows the results of the analysis without any purchases in the markets, Figure 5 extends this with results for the situation where limited purchase is possible. The columns are grouped for each market combination given in *Markets*. Note that the DA-only runs are equal independent of *Trade modes* when production capacity is included, since no limit are assumed for sale in DA and no purchase is profitable for the producer in DA-only since there are no sales price exceeding a purchase price. The last argument also implies that *Pure market trade* with DA-only gives zero profit. All columns in the figure shows the added value from the reference analysis where only the DA market is available. Each group of columns represent the four *Trade modes*. As the figure illustrates, there is a substantial added value for multi-market limited sale and purchase, compared to the limited sale only. This is particularly evident for the analyses including the BM market. The added value of multi-market limited sale for each market combination is 0.5%, 2.8% and 3.3% relative to DA-only profit, respectively. When also allowing limited purchases, the value further increases, for each of the three groups respectively, with 0.3%, 5.9% and 6.3%. Also when including purchase, the added value is large for BM and relatively small for ID.

The leftmost column in each group, showing the profit achieved when only utilizing the arbitrage opportunities within the trade limits, provides an insight in where the largest value is created in our analysis. *Pure market trade* captures within hour arbitrage only, since a zero net market position is enforced in each hour. For DA-only the *Pure market trade* profit is zero since the cleared market price in DA gives no room for arbitrage. We do not observe any significant increase in the value of limited sale and purchase with a production system available relative to *Pure market trade*. This shows that there is no added value from time swaps utilizing the storage capacity due to a multi-market operation. It is important to note that there is, in general, value from time swaps. In our analysis this is captured in the DA trade, and no additional value from time swaps based on access to multiple markets are observed. Given the high correlation between the prices in the markets, the value of utilizing the reservoir to move production from hours with low price to hours with high price has already been exploited by the DA planning. Remaining arbitrage opportunities due to price differences between the markets within the same hour can be accomplished without changing the production levels. This result is illustrated by the small differences between the first and fourth column for each of the groups in Figure 5.

As observed by the *Pure market trade* results, there are substantial within hour arbitrage opportunities present in the historical market data used in this analysis. Table V indicates the extent of these arbitrage opportunities measured by how frequently a sale price exceeds a purchase price at the same time as the trade limit is larger than zero in both trade directions. Since the DA price is given by an hourly market clearing, there is naturally no within market arbitrage opportunities in this market. For both the ID and BM, however, there are small within market arbitrage possibilities (hours where some trades have had higher sales price than the purchase price of other trades). In sum, this arbitrage possibilities give a profit potential of 0.5 % and 0.1 % relative to DA-only profit for the ID and BM respectively, when taking the trade limits into account. As is evident from Table V, the potential for arbitrage trades between the markets are larger, and constitute the main source for the *Pure market trade* values in Figure 5.

The results from our analysis shows the potential values that

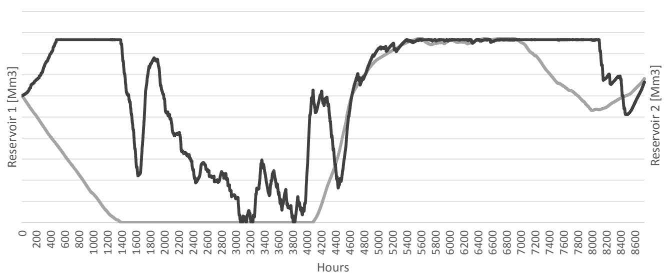

Fig. 6. Example of reservoir trajectories for the Limited sale & buy model run with all markets included.

TABLE V
PERCENTAGE OF THE HOURS WHERE SALE PRICE EXCEEDS PURCHASE PRICE WITHIN AND BETWEEN MARKETS.

		Buy		
		DA	ID	BM
Sale	DA	0 %	10 %	35 %
	ID	12 %	2 %	8 %
	BM	30 %	5 %	1 %

could be achieved given perfect foresight and optimal trades in the markets during a year. Naturally, these assumptions are not realistic, and a producer would not be able to fully realize the arbitrage-based profits that we have identified from participation in multiple well-functioning markets. The main motivation for our analysis has however been to highlight where the potential value-creation from participation in multiple markets is, given todays market designs and prices. Additionally, hydropower production is highly flexible, and in a substantial part of the time the cost of changing the production level on short notice is relatively low. This cost structures makes it possible to adapt to changing market prices and thereby realize parts of the observed values.

The reservoir levels for the two reservoirs included in our analysis is shown in Figure 6. As can be seen from the reservoir profiles, there are several hours where the reservoirs are either depleted or completely full. This is another consequence of our perfect foresight assumption. Even though the underlying production system is modelled in detail in the analysis model, the ability of the models to perfectly predict the future allow them to make extreme decisions. Naturally, adding uncertainty to our analysis would change these results and also reduce the profit levels that we report in this paper. We have found upper bounds on the total profits that are achievable from trading in the DA market separately, and by trading in multiple-markets. It might however be that the potential value of trading in multiple markets (defined as the difference between participating in multiple markets and only participating in the DA market) can be even higher when adding uncertainty to the analysis. This will be a topic for future research.

IV. CONCLUDING REMARKS

We have presented an case study estimating bounds on the added value a price-taking hydropower producer can achieve by participating in multiple short-term energy markets over a year. The study uses a detailed representation of a real Norwegian hydropower plant and historical market prices and quantity limits from 2015. Three markets are included, day-ahead (DA), intra-day (ID) and the balancing market (BM). The study assumes perfect foresight over the whole model horizon, which is a simplification that gives an upper bound on the profit in each model run. This approach has the strength of substantially reducing the complexity relative to a full-scale three-market stochastic model, and forms a basis for assessing the potential value of developing more complex models. The results show a significant added value from selling in multiple markets relative to DA-only, reaching 3.3% with both ID and BM trades limited by historical trade quantities. This value increases with increasing trade quantity limits. Modelling both purchase and sale in ID and BM allows the model to utilize arbitrage opportunities given by the market prices, and brings the added value from multi-market trade to 9.6%. In both situations the BM market has the largest impact, which can be explained by a combination of larger trade limits and more extreme prices. This indicates that in the market situation in Norway as of 2015, focusing on optimal trading in BM has a larger potential value than trading in ID. Further work will take two directions. A similar case study will be conducted to assess how the potential values of multi-market trade are affected by different price and trade limit assumptions. This is motivated by the expectation of increasing price volatility and larger volumes in the short-term markets due to increasing shares of intermittent production. The other direction is to gradually remove the simplifying perfect foresight assumption by first introducing a rolling horizon and limited foresight, and next utilize a stochastic model to properly capture the uncertainty in future market prices.

ACKNOWLEDGMENT

The authors would like to thank the Norwegian Research Council for funding through the research grant 243964/E20.

REFERENCES

[1] Entso-E, "Network codes - Capacity allocation and congestion management." [Online]. Available: https://www.entsoe.eu/major-projects/network-code-development/capacity-allocation-and-congestion-management/Pages/default.aspx

[2] ——, "Network codes - Electricity balancing." [Online]. Available: https://www.entsoe.eu/major-projects/network-code-development/electricity-balancing/Pages/default.aspx

[3] E. Faria and S.-E. Fleten, "Day-ahead market bidding for a Nordic hydropower producer: taking the Elbas market into account," *Computational Management Science*, vol. 8, pp. 75–101, 2011.

[4] G. Klæboe, "Stochastic short-term bidding optimisation for hydro power producers," Ph.D. dissertation, Norwegian University of Science and Technology, 2015:176 2015.

[5] M. Fodstad, A. Helseth, and A. L. Henden, "Hydropower scheduling in day-ahead and balancing markets," in *Proceedings of 12th European Energy Markets, Lisbon*, May 2015.

[6] T. K. Boomsma, N. Juul, and S.-E. Fleten, "Bidding in sequential electricity markets: The Nordic case," *European Journal of Operational Research*, vol. 238, no. 3, pp. 797–809, 2014.

[7] Shop info site. Accessed February 2017. [Online]. Available: http://www.sintef.no/en/software/shop/

[8] O. B. Fosso and M. M. Belsnes, “Short-term hydro scheduling in a liberalized power system,” in *International Conference on Power System Technology*, vol. 2, 2004, pp. 1321–1326.