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# Economic potential of industrial demand side management in pulp and paper industry

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## Abstract

Increasing levels of variable renewable energy require additional flexible resources in the global energy system. In countries with energy-intensive industries, flexibility may be increased through industrial demand side management (IDSM). In most studies, the potential of IDSM is estimated from a technical or theoretical viewpoint. However, IDSM capacity is only utilized if the industry finds it profitable, and thus the economic potential should also be assessed. The focus of this paper is on the intra-day IDSM potential of a paper mill site that is active in the Nordic power market. An optimization model is built to estimate the costs that occur when the paper mill executes regulating power bids, if the original production schedule has been optimized against a spot price forecast. The costs are estimated for different sizes of bids and a marginal cost curve is provided for pricing them. Using this marginal cost curve, the market potential of the case mill site is assessed. It is found that this potential is greatly influenced by the costs of executing regulating power bids. The results indicate that transmission system operators and policy makers should account for economic factors when assessing the potential of market based IDSM.

*Keywords:* demand side management, flexible demand, price volatility, mechanical pulp production, regulating power market

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## 1. Introduction

Mitigation of the climate change is a common goal in the European energy policy and actions limiting the global warming have been taken globally [1]. Many countries have adopted policies to encourage the increase of renewable energy in energy production [2]. Variable renewable energy technologies, in particular wind and solar power, are becoming common around the world. High penetration levels of these technologies will require additional flexible resources in the energy system [3]. The trend of growing variable renewable electricity production is visible in Finland, where the wind production was 2.3 TWh in 2015, growing by 110 % from the year before [4].

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In the Nordic countries, matching the demand and supply of electricity is managed through electricity markets on different timescales [5]. Companies can minimize costs or maximize profits by affecting their consumption or production of electricity according to the market price of electricity. In particular, timing the total electricity consumption to low market prices is referred to as demand side management (DSM). Also changes in the preplanned consumption for an economic benefit are part of DSM. Large potential for industrial DSM (IDSM) has been identified in the German energy-intensive industries [6]. In Finland, company interviews on the utilization of IDSM revealed unused potential, especially in energy-intensive industries [7].

In this paper, the economic DSM potential of the mechanical pulp production process of a Finnish pulp and paper mill site is studied, when the paper production schedule is fixed. A mathematical model is presented for assessing the technical costs of the mill site flexibility in the form of implemented regulation market bids. The case site operates many loosely coupled and energy-intensive processes, which makes it a good example of an industrial site with high potential for IDSM, but the cost of which is difficult to assess due to the complexity of the process interdependencies. The short term flexibility of the plant lies in mechanical pulping machines which, in theory, can be turned off and on quickly without disturbing the site's paper production process due to mass storages on the site. Many continuous processes, however, work better if they are run at a constant rate without stops [8]. Indeed, from the site's viewpoint, the flexibility potential is realized only if the total cost of production can be significantly decreased or profit increased.

Specifically, the optimization model is used to estimate a bidding curve for regulating power bids (RPBs) of different sizes. This allows further simulation of the site's market behavior within a large market data sample consisting of 24-hour periods in 2014. It is found that only a fraction of the site's over 80 MW DSM capacity is expected to participate in the Finnish regulating power market. In addition, several factors are discussed that are not explicitly captured by the model, but which decrease the site's DSM potential further, such as the risks of schedule changes. Due to these factors the results presented in this paper represent the best case scenario or maximum potential for DSM by the mechanical pulping machinery on the site.

Even in the light of these limitations, the DSM potential of the mechanical pulping process is considerable for grid balancing. This study helps decision makers like transmission system operators (TSOs) and authorities understand how DSM can be seen from an industrial player's point of view. Analyses based on pure technical assessments have the potential to give accurate results about the total flexible capacity, but unless the economic incentives for flexibility are accounted for, the cost of activating it to the market remains unclear.

This paper is structured as follows. First, in Section 2, the existing literature is reviewed. In Section 3, the case mill site is described. In Section 4, the optimization model for mechanical mass production in the mill site is formulated. In Section 5, the model's results are presented. In Section 6, the results and their implications are discussed, and Section 7 concludes.

## 2. Literature review

### 2.1. Demand side management

Increasing amounts of variable renewable electricity affect the security aspects of current electric systems, e.g. the balancing of supply and demand in the grid [9]. Variability of wind power in the European Union is studied in [10] and the forecasting of electricity load is discussed in [11]. Zakeri et al. [12] model the maximum share of renewable energy in the current Finnish energy system.

Flexibility in the demand of electricity requires that consumers execute DSM actions. In DSM, the aim is not to reduce the overall consumption of energy, but to consume it at the right time with respect to the fluctuating price of electricity. Additionally, DSM contains the concept of demand response, in which changes in consumption are made in response to current events on the market [13]. Examples of such responses are rescheduling consumption or cancelling it for the time being. A review of the current state and barriers of IDSM are presented in [14].

The focus of this paper is on the economic short-term DSM potential of mechanical pulp production. Literature on the short-term flexibility of industrial processes is often done from the top-down perspective with little focus on economic analysis. Gils [15] assesses the theoretical demand response potential in Europe through literature-based technical capabilities of different processes. Shiljkut and Rajakovic [16] present a method for estimating demand response potential by comparing daily consumption profiles on different years. Paulus and Borggreffe [6] utilize literature and interviews with company representatives in their research on the potential of DSM in Germany. The authors also consider estimates for costs caused by DSM on industrial processes. For mechanical pulp production they have estimated investment costs of 12–15 €/kW, variable costs of less than 10 €/MWh and no fixed costs. This work, focusing on the cost of short-term DSM only, indicates higher variable costs. Zareen et al. [17] propose a real-time cost-benefit model for demand response in a microgrid network.

The costs caused by DSM actions can be direct or indirect, such as lost revenue or increased workforce cost, respectively. Direct costs may be easier to calculate. Indirect costs can be modeled by adding suitable penalties to schedule changes [18]. Due to these often uncertain costs, the actual price limits of DSM actions are separate from the measurable costs. In practice, they depend on the timeframes and volumes of the actions. The demand response potentials in the Finnish industry considering price, reaction time and duration are studied in [19].

The scheduling and rescheduling of production processes has a key role in both the cost and potential of IDSM. The scheduling of a paper mill site includes the planning of pulp, paper and energy production. The level of coupling between these processes depends on the storage capacities of different intermediate products [20]. It is common to make production plans manually at the site, often hierarchically and iteratively [21]. The optimality of the resulting plan can not be guaranteed because only few alternatives are

considered. For example, in manual hierarchical planning between pulp and paper production it has been noted that backlogging and inventory costs are often improperly weighted [22].

Software and models have been developed to support the decision making of paper mills. Figueira et al. [23] develop a decision support system for pulp and paper production that assists a planner in creating an optimal lot size and schedule. The model included in the system is more detailed than the model presented in this work, considering e.g. the material flows of pulp, black liquor, and broke paper in some detail. Hadera et al. [24] present a decomposition strategy for steel production scheduling that allows result quality versus computation time to be controlled.

Optimized operation of a CHP plant of a pulp and paper mill is studied in [25]. Rong et al. [26] present a unit decommitment algorithm for convex CHP plant production planning. The same methodology is used in this paper for CHP plant modeling. Makkonen and Lahdelma [27] extend this methodology to non-convex CHP plant modeling. Jüdes et al. [28] utilize mixed integer nonlinear programming for the modeling of partial-load operation of a CHP plant.

As described above, the research approach on the potential of IDSM is often top-down, based on e.g. technical specifications or company interviews. On the other hand, relevant bottom-up modeling work is typically aimed at improving plant operations, not for assessing IDSM potential. In this paper, the resulting gap is bridged by using a bottom-up model for assessing the IDSM potential of a pulp and paper mill. This method gives a more realistic estimation of the economic potential of IDSM than purely technical top-down estimates, and is lighter to utilize than a highly detailed bottom-up model. In addition, the method gives insight on the difference between the technical and economic potentials of IDSM. The insights in this paper can be especially valuable regarding plants currently in operation, because it is based on actions in one area of operation (pulp production), and not in a complete overhaul of plant management.

## *2.2. Electricity market in the Nordic countries*

The electricity markets relevant to this paper are the day-ahead Elspot market (spot market), the Elbas market (intra-day market), and the regulating power market. After each hour of delivery, participants need to compensate for imbalances between their agreements on each market and actual operation.

Elspot of Nord Pool Spot is the main power market in the Nordic countries. Bids to buy and sell electricity are left every day by 12:00 CET for each hour of the following day, and they are processed in a closed auction. The bids are conditional bids to buy or sell if the market price is lower (or equal) or higher (or equal) than the price requirement of the bid, respectively [5].

Elbas is an intra-day market for trading power, also operated by Nord Pool Spot. It supplements the Elspot market and helps companies match the consumption and supply of electricity. Elbas is a continuous market in which trading takes place every day on every hour until one hour before delivery. Bids to buy

and sell electricity are matched as soon as bids with compatible price limits are made [7]. Thus, the actual price of electricity on any hour can vary during trading.

To regulate the power balance of the electric grid, the TSOs of the Nordic countries manage a regulating power market with a common merit order bidding list. Bids for up- or down-regulation can be submitted for all resources which can implement a power change of at least 10 MW within 15 minutes from the activation order [7]. The power change must be available for the duration of one hour. In up-regulation, the TSO purchases electricity from the company, and in down-regulation the TSO sells it to the company. A bid can be either an increase or a decrease in either production or consumption of electricity, but it can not be a combination of them.

A price limit is set for all RPBs (€/MWh), but the realized price is only known after the operating hour. The price of up-regulation is the highest price limit of any accepted up-regulating bid on that hour, and the price of down-regulation is the lowest price limit of any accepted down-regulating bid on that hour [5]. The RPBs must be submitted to the TSO at least 45 minutes before the target hour [7].

The regulating power market is different from the other described markets, because it is essentially a capacity market: Instead of planning to either run or not run a process, the participant must be prepared to run the process, and also do so when not otherwise instructed by the TSO. Moreover, options for preparing for the regulation are limited, as the lead time from order to execution is short, and no other electricity market is available for the time span of the regulation. Potential corrections to long-term operation must therefore be done for hours after the regulation utilizing any of the described markets.

### 3. Case site

The case site is a large pulp and paper mill site located in Finland. Included in the analysis are three paper machines and a number of different grinding machines (GM). Grinding machines include machinery for thermomechanical pulp (TMP), groundwood (GW) and pressurized groundwood (PGW). The site's CHP power plant is also considered in the analysis. The analyzed processes are generally described in Figure 1. The processing of mechanical mass happens in and between a series of processing and storage towers, as illustrated in Figure 2 through an exemplary process. Because the processing line structure is business sensitive, Figure 2 is only indicative of the real size and complexity of the processing network.

In a paper machine, paper is formed from a combination of different pulp types through mechanical and thermal drying. The process requires electricity and considerable amounts of steam. In TMP production, wood fibers are separated from each other by mechanical force in a disc refiner. The process is energy-intensive, with a single refiner consuming 10–30 MW of electric power [29]. A single processing line can have 1–3 refiners. Normally around two thirds of the refining energy can be recovered as steam. After refining, the pulp goes through latency (curliness) removal, screening, mixing and bleaching before final storage.

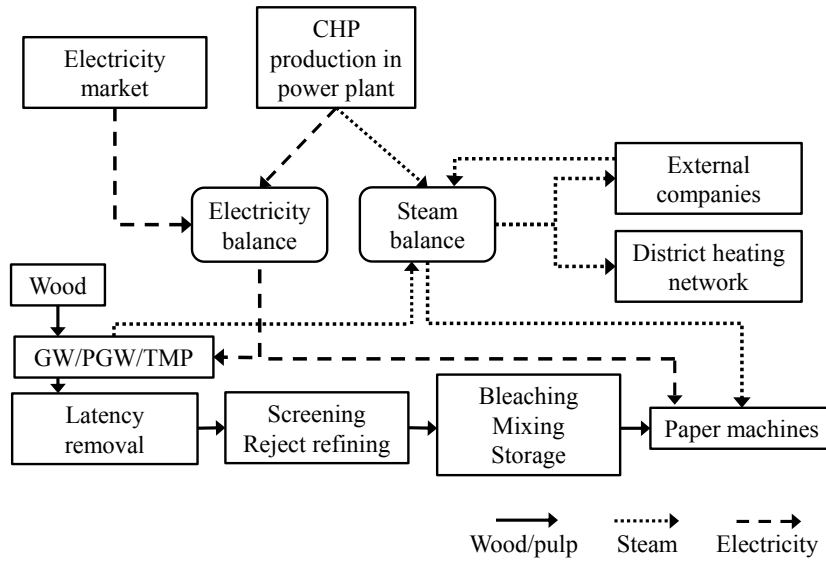


Figure 1: An illustration of the main energy and material flows in the case mill site. Energy flows from and to the mill site are also shown.

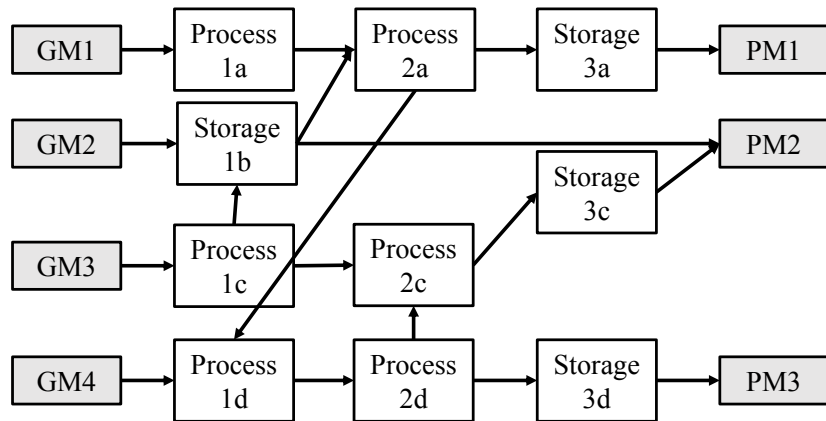


Figure 2: An illustration of the mechanical mass processing network. The names 1a–3d represent different process stages and storages for context, since the exact connections and process names are business sensitive.

The production of GW happens in a grinding process, where debarked logs are pressed sideways against a rotating cylinder. Steam is not typically produced in the GW process. If the GW process happens under increased pressure, it is referred to as PGW. In this work, both groundwood types are referred to as GW. The production process of GW after initial grinding is similar to that of TMP, but latency removal does not happen in a separate tower like with TMP.

The case site power plant is a CHP plant utilizing biomass, oil, and coal. The power plant is used for both industrial and residential heat generation and the modeling in this paper is based on i) the design of the

power plant as a whole, ii) the production of steam and electricity that is the mill site’s share of production, and iii) the district heat (DH) production of the plant. The DH production is not affected by the case company, but it is considered in this paper due to its effect on the power plant production as a whole. The power plant’s electric power production capacity is remarkably smaller than the typical consumption of the mill site.

The case power plant typically operates with either one or two boilers depending on season and maintenance. It produces middle pressure (10 bar) and low pressure (3 bar) steam for the paper mill. Both pressure levels of steam are also generated in the TMP processes. Low pressure steam can additionally be purchased from and sold to external companies nearby. There is a single back pressure turbine with middle and low pressure extraction valves. High pressure steam can be reduced to middle or low pressure steam through pressure reduction valves. In line after these, there are desuperheaters that add water to the pressure reduced stream. Additional water lowers the steam temperature while adding to the mass flow of the stream. Production and consumption of steam is balanced by the steam bars and two short term steam accumulators between the middle and low pressure levels. Steam can also be vented out of the plant.

#### 4. Optimization model and calculation process

First, the base case optimization model is formulated for scheduling mechanical mass production for a 24-hour period with a predetermined paper production schedule. Then, it is explained how the model is used in this work to calculate the cost of implementing RPBs at the site. An illustrative example follows.

##### 4.1. Objective function

The objective function is the cost of operation for the paper mill and power plant during the planning period. The objective function is given by

$$\min \sum_{i=1}^T (E_{\text{spot}}^i - E_{\text{rev,id}}^i + F_{\text{cost}}^i + S_{\text{pur,3bar}}^i S_{\text{price,3bar}} + S_{\text{incrProd}}^i S_{\text{incrProd,cost}}) T_{\text{step}} + R_{\text{DH}} + R_{\text{S}} + R_{\text{M}}, \quad (1)$$

where  $E_{\text{spot}}^i$  is the cost of purchased spot electricity,  $i$  is the timestep,  $E_{\text{rev,id}}^i$  is the revenue from the intra-day market,  $F_{\text{cost}}^i$  is the fuel cost of the plant,  $S_{\text{pur,3bar}}^i$  and  $S_{\text{price,3bar}}$  are the amount and price of purchased steam, respectively,  $S_{\text{incrProd}}^i$  and  $S_{\text{incrProd,cost}}$  are the amount and cost of increased power plant heat production (see Equation (4)),  $T_{\text{step}}$  is the length of the timestep of the calculation,  $T$  is the last timestep of the modeling period, the timestep indices  $i, i_1, i_2, i_3$  in the superscript of parameters or variables mean that they are time-dependent, and  $R_{\text{DH}}$ ,  $R_{\text{S}}$ , and  $R_{\text{M}}$  are small penalty costs related to DH, steam, and mechanical mass processes, respectively. The penalty costs are small enough not to affect the core operation of the model, but high enough to make model results consistent between model runs. Without



the penalty costs, some variables would vary between runs, e.g. the pressure of vented out steam would be 3 bar on one run and then 10 bar on another run, or mechanical mass would be moved on hours 1 and 2 on one run, and then on hours 2 and 3 on another. These changes would have no effect on the core results, but would make analysing results more difficult.

## 4.2. Basic constraints

### 4.2.1. CHP plant

The CHP power plant model is similar to that presented in [26]. The model is based on the assumption that if the power plant can operate in two points that are combinations of heat production, electricity production and fuel consumption, then it can also operate in any convex combination of them. In this paper, a set of extremal operating points have been estimated from historical data, that enclose the most common operating points of the plant. The modeled plant can operate in any point that is a convex combination of the extremal operating points. The following equations describe the operating point model:

$$CHP^{Dc,i} = \sum_{k \in K_{op}} \lambda_{CHP}^{k,i} K_{CHP}^{k,Dc} \quad \forall i \forall Dc, \quad (2)$$

$$\sum_{k \in K_{op}} \lambda_{CHP}^{k,i} = 1 \quad \forall i, \quad (3)$$

$$\lambda_{CHP}^{k,i} \geq 0 \quad \forall i \forall k.$$

where  $CHP^{Dc,i}$  contains the values of the power plant's operating points, and  $K_{CHP}^{k,Dc}$  contains data of the extremal operating points. The variable  $CHP^{Dc,i}$  is the convex combination of all extremal operating points  $K_{op}$ ,  $\lambda_{CHP}^{k,i}$  is the weight factor that determines how much each extremal operating point is weighted in the modeled operating point, and  $Dc \in Dc_{set}$  is the set of dimensions for the operating points: "heat", "elec", and "fuel".

The model may freely divide the total heat production to different steam pressure levels and DH, with certain limits determined from historical data. This simplification is expected to affect the economics of some operating points, but not the technical flexibility of the plant, due to several available routes of heat production. In addition, the heat production of the power plant is relaxed by allowing additional heat production that does not depend on the operating point. This production ( $S_{incrProd}^i$ ) is assumed to be technically feasible, and is set to cost significantly more than other means of procuring steam or DH. The total heat production ( $CHP^{heat,i}$ ) of the power plant is constrained by

$$CHP^{heat,i} + S_{incrProd}^i = \sum_{Dq \in Dq_{set}} Q_{prod}^{Dq,i} \quad \forall i, \quad (4)$$

where  $Q_{prod}^{Dq,i}$  is the production of heat component  $Dq \in Dq_{set}$  (10bar, 3bar, DH).

The steam powers in Equations (5)–(7) are based on the heat power fed into processes on each steam pressure level. The condense steam is utilized in processes that are not included in the model.

The following equations define the power balances of steam:

$$\sum_{j \in J} (S_{\text{gen},2\text{bar}}^j - S_{\text{cons},2\text{bar}}^j) Y^{j,i} + S_{\text{red},3\text{bar}}^i = S_{\text{vent},2\text{bar}}^i \quad \forall i, \quad (5)$$

$$Q_{\text{prod}}^{3\text{bar},i} + S_{\text{pur},3\text{bar}}^i + S_{\text{red},10\text{bar}}^i = \sum_{j \in J} S_{\text{cons},3\text{bar}}^j Y^{j,i} + S_{\text{vent},3\text{bar}}^i + S_{\text{red},3\text{bar}}^i + S_{\text{sold},3\text{bar}}^i \quad \forall i, \quad (6)$$

$$Q_{\text{prod}}^{10\text{bar},i} = \sum_{j \in J} S_{\text{cons},10\text{bar}}^j Y^{j,i} + S_{\text{vent},10\text{bar}}^i + S_{\text{red},10\text{bar}}^i \quad \forall i. \quad (7)$$

The variables and parameters for each steam level are denoted similarly. For 2 bar steam  $S_{\text{gen},2\text{bar}}^j$  is the generation of steam in each machine  $j$ , for 3 bar steam  $S_{\text{cons},3\text{bar}}^j$  is the consumption of steam,  $S_{\text{vent},3\text{bar}}^i$  and  $S_{\text{red},3\text{bar}}^i$  are the venting and reduction of steam, respectively,  $Q_{\text{prod}}^{3\text{bar},i}$  is the production in the power plant,  $S_{\text{pur},3\text{bar}}^i$  and  $S_{\text{sold},3\text{bar}}^i$  are the amounts of purchased and sold steam, respectively, and the variable  $Y^{j,i}$  is a binary ON/OFF variable for each machine.

To make the steam purchases realistic from the steam producer's viewpoint, the purchases are limited in the model by a maximum amount and rate of change by

$$S_{\text{pur},3\text{bar}}^i \leq S_{\text{pur,max}} \quad \forall i \quad (8)$$

and

$$-S_{\text{pur,ch,max}} \leq S_{\text{pur},3\text{bar}}^i - S_{\text{pur},3\text{bar}}^{i+1} \leq S_{\text{pur,ch,max}} \quad \forall i \leq T - 1, \quad (9)$$

where  $S_{\text{pur,max}}$  and  $S_{\text{pur,ch,max}}$  are the maximum purchased power and maximum hourly change of purchased power for 3 bar steam, respectively.

District heating is balanced by equation

$$Q_{\text{prod}}^{DH,i} = DH_{\text{req}}^i + DH_{\text{cooling}}^i \quad \forall i, \quad (10)$$

where  $Q_{\text{prod}}^{DH,i}$  is DH production of the power plant,  $DH_{\text{req}}^i$  is the DH demand and  $DH_{\text{cooling}}^i$  is the amount of additional cooling of DH water. Cooling is included to create an option of overproduction in all heat components.

Electricity balance is described by

$$CHP^{\text{elec},i} + E_{\text{pur}}^i = \sum_{j \in J} E_{\text{cons}}^j Y^{j,i} \quad \forall i, \quad (11)$$

where  $CHP^{\text{elec},i}$  is the electricity production in the power plant and  $E_{\text{cons}}^j$  is the electricity consumption of each machine.

#### 4.2.2. Spot purchase

The cost of electricity purchased from the spot market ( $E_{\text{spot}}^i$ ) is calculated differently when running the model for planning and implementing the RPB (see Section 4.3). The cost is determined by the equations

$$E_{\text{spot}}^i \geq E_{\text{pur,noreg}}^i E_{\text{price}}^i \quad \forall i \quad (12)$$

and

$$E_{\text{spot}}^i (1 - \text{Reg}_{\text{scen}}) \geq E_{\text{pur}}^i E_{\text{price}}^i (1 - \text{Reg}_{\text{scen}}) \quad \forall i. \quad (13)$$

Here,  $E_{\text{price}}^i$  is the price of electricity (the forecast or realized spot price appropriately),  $E_{\text{pur,noreg}}^i$  is the purchased amount of electricity from the spot market (zero in initial planning), and  $\text{Reg}_{\text{scen}}$  is a binary variable with the value 1 if a RPB is being implemented and 0 otherwise. In all use cases, one of Equations (12) and (13) is trivially satisfied.

#### 4.2.3. Mechanical mass balances

Mass balance equations are defined for a system which consists of a number of storage and processing towers connected to mass consuming and producing machines. The equations can accommodate a variety of different connections and capacities.

Moving mass between storages can be represented by the equation

$$M_{\text{move}}^{i,u_1 \rightarrow u_2} = M_{\text{rec}}^{u_1,u_2} \sum_{u_3 \in U} M_{\text{move}}^{i,u_3 \rightarrow u_2} \quad \forall u_1, u_2 \forall i, \quad (14)$$

where the parameter  $M_{\text{rec}}^{u_1,u_2} \in [0, 1]$  is a recipe parameter that defines what fraction of mass that is moved to  $u_2$  must come from  $u_1$ .

The total amount of mass ( $M_{\text{stor,total}}^{u_1,i_1}$ ) in each storage and processing tower ( $u_1, u_2 \in U$ ) can be calculated by

$$\begin{aligned} M_{\text{stor,total}}^{u_1,i_1} = & M_{\text{stor,init}}^{u_1} + \sum_{i_2=1}^{i_1} \left\{ \sum_{j \in J} (M_{\text{prod}}^j - M_{\text{cons}}^j) \text{Rec}^{j,u_1} Y^{j,i_2} \right. \\ & \left. + \sum_{u_2 \in U} (M_{\text{move}}^{i_2,u_2 \rightarrow u_1} - M_{\text{move}}^{i_2,u_1 \rightarrow u_2}) \right\} T_{\text{step}} \quad \forall u_1 \forall i_1, \end{aligned} \quad (15)$$

where  $M_{\text{stor,init}}^{u_1}$  is the initial stored amount of mechanical mass,  $M_{\text{prod}}^j$  and  $M_{\text{cons}}^j$  are mass productions and consumptions of machines,  $\text{Rec}^{j,u_1} \in [0, 1]$  sets the recipe by which mass is moved between machines and towers, and  $M_{\text{move}}^{i_2,u_1 \rightarrow u_2}$  is the amount of mass moved from tower  $u_1$  to tower  $u_2$ . The allowed amount of stored mass in each tower is set by the size of the tower and the need to reserve either space or mass in towers for unforeseen events. The end storage is also constrained in each tower.

Some processes in towers take more time than one timestep. The amount of mechanical mass that is ready to be moved ahead from a tower ( $M_{\text{stor,ready}}^{u_1, i_1}$ ) is calculated by the equation

$$\begin{aligned}
M_{\text{stor,ready}}^{u_1, i_1} = & M_{\text{stor,init}}^{u_1} + \sum_{i_2=1}^{i_1 - M_{\text{delay}}^{u_1}} \left\{ \sum_{j \in J} [(M_{\text{prod}}^j - M_{\text{cons}}^j) \text{Rec}^{j, u_1} Y^{j, i_2}] \right. \\
& + \sum_{u_2 \in U} (M_{\text{move}}^{i_2, u_2 \rightarrow u_1} - M_{\text{move}}^{i_2, u_1 \rightarrow u_2}) \left. \right\} T_{\text{step}} \\
& - \sum_{i_2 = i_1 - M_{\text{delay}}^{u_1}}^{i_1} \left\{ \sum_{j \in J} [M_{\text{cons}}^j \text{Rec}^{j, u_1} Y^{j, i_2}] \right. \\
& \left. + \sum_{u_2 \in U} M_{\text{move}}^{i_2, u_1 \rightarrow u_2} \right\} T_{\text{step}} \quad \forall u_1 \forall i_1,
\end{aligned} \tag{16}$$

where the processing time in a tower ( $M_{\text{delay}}^{u_1}$ ) is given as an integer amount of time steps the process takes.

To guide how mechanical mass is stored and processed, a maximum allowed rate of change has been assigned for each tower. The limit is not strict, but rapid changes are penalized by small costs that depend linearly on the penalizable change for each hour. Different towers have separate penalty factors, which allows the prioritization of the stability of certain towers' surface levels for realistic operation. This does not affect the production scheduling due to small penalties.

For a GW line to be running, a minimum amount of stones must be running. This limitation is implemented by the following equations:

$$GW_{\text{stonesON}}^{i, l_{\text{GW}}} - GW_{\text{active}}^{i, l_{\text{GW}}} A_{\text{GW}} \leq 0 \quad \forall i \forall l_{\text{GW}} \tag{17}$$

and

$$GW_{\text{stonesON}}^{i, l_{\text{GW}}} + (1 - GW_{\text{active}}^{i, l_{\text{GW}}}) A_{\text{GW}} \geq GW_{\text{stones, min}}^{l_{\text{GW}}} \quad \forall i \forall l_{\text{GW}}. \tag{18}$$

Here,  $GW_{\text{stonesON}}^{i, l_{\text{GW}}}$  is the amount of stones that are running,  $GW_{\text{active}}^{i, l_{\text{GW}}}$  is a binary variable representing the line ( $l_{\text{GW}} \in l_{\text{GW, set}}$ ) being running (1) or stopped (0),  $A_{\text{GW}}$  is a sufficiently large positive integer,  $GW_{\text{stones, min}}^{l_{\text{GW}}}$  is the required minimum amount of stones running.

#### 4.3. Calculation process

First, the mill site purchases electricity from the spot market for the following day based on their best knowledge at that point in time. Costs are then calculated for that plan but with realized electricity prices. In the modeling, this is compared with the situation that a certain regulating bid by the mill site is accepted. The bid acceptance causes lost mechanical mass production. The lost production is assumed to be compensated for within 24 hours. For this purpose, the intra-day electricity market can be utilized. All these actions are represented in the following formulation.

The calculation of the cost of regulation can be divided into four steps: three runs of the model, and a final calculation step. The steps will be presented next, along with additional constraints for Step 3.

*Step 1: Forecast*

The model is solved with a forecast for electricity spot price. The result is an hourly production schedule for both CHP plant and mass production machinery for a 24-hour period. The constraints presented in Section 4.2 are used. The variable  $E_{\text{rev,id}}^i$  (revenue or cost from intra-day trading) is naturally zero.

*Step 2: Optimized plan with realized prices*

The exact production plan created in Step 1 is kept, but the price of electricity is changed to the realized spot price of electricity. This produces the realized cost of the operation that was planned according to the price forecast.

*Step 3: Implementation of a regulating power bid*

Here, the production plan of Steps 1 and 2 is modified due to an accepted RPB on the first hour of the modeling period. Additional constraints described in Equations (19)–(24) are applied.

The decrease in electricity purchases from Step 2 to Step 3 during regulating hours (to implement the RPB) is given by

$$E_{\text{pur}}^i = E_{\text{pur,noreg}}^i - E_{\text{reg,vol}} \quad i \in \text{Reg}_{\text{hrs}}, \quad (19)$$

where  $E_{\text{pur}}^i$  is the purchased electricity during the solve, and  $E_{\text{pur,noreg}}^i$  is the electricity purchased in Steps 1 and 2,  $\text{Reg}_{\text{hrs}} \subset T_{\text{set}}$  is the set of regulating hours, and  $E_{\text{reg,vol}}$  is the time-invariant amount of sold regulating power, which is a variable constrained to match the RPB size limits as described later.

The total amount of intra-day purchases ( $E_{\text{pur,id,total}}^i$ ) is calculated from the change in electricity purchases between Steps 2 and 3. Intra-day purchases are forbidden during the regulating hours. These two constraints are set by the following equations:

$$\begin{aligned} E_{\text{pur,id,total}}^i &= 0 & \forall i \in \text{Reg}_{\text{hrs}}, \\ E_{\text{pur,id,total}}^i &= E_{\text{pur}}^i - E_{\text{pur,noreg}}^i & \forall i \notin \text{Reg}_{\text{hrs}}. \end{aligned} \quad (20)$$

The total purchased amount of intra-day electricity is divided into three blocks to allow different pricing of different sizes of purchases or sales.

$$\begin{aligned} E_{\text{rev,id}}^i &= - \left( E_{\text{pur,id,b1}}^i E_{\text{price1,id}}^i + E_{\text{pur,id,b2}}^i E_{\text{price2,id}}^i \right. \\ &\quad \left. + E_{\text{pur,id,b3}}^i E_{\text{price3,id}}^i \right) \text{Reg}_{\text{scen}} \quad \forall i, \end{aligned} \quad (21)$$

where for block 1,  $E_{\text{pur,id,b1}}^i$  is the purchased amount of intra-day electricity and  $E_{\text{price1,id}}^i$  is the price of intra-day electricity. An identical term exists for each of the three blocks. The estimation of the price of

intra-day electricity is described in Section 4.4. The total intra-day purchase  $E_{\text{pur,id,total}}^i$  is constrained by

$$E_{\text{pur,id,total}}^i = E_{\text{pur,id,b1}}^i + E_{\text{pur,id,b2}}^i + E_{\text{pur,id,b3}}^i \quad \forall i, \quad (22)$$

where the variable  $E_{\text{pur,id,total}}^i$  can only hold integer values, i.e. intra-day purchases and sales are integer-sized. The total intra-day purchases are also limited by the following equations:

$$Reg_{\text{dir}} \sum_{i \in T_{\text{set}}} E_{\text{pur,id,total}}^i \leq \sum_{i \in Reg_{\text{hrs}}} E_{\text{reg,vol}}, \quad (23)$$

and

$$Reg_{\text{dir}} E_{\text{pur,id,b1}}^i \geq 0 \quad \forall i. \quad (24)$$

Here,  $Reg_{\text{dir}}$  is the regulation direction (1 for up-regulation and  $-1$  for down-regulation). Equation (23) sets the maximum total volume of intra-day purchases to the total volume of the RPB. Equation (24) sets the direction of intra-day trading for block 1 to be opposite to the direction of regulation. An identical equation to Equation (24) is written for  $E_{\text{pur,id,b2}}^i$  and  $E_{\text{pur,id,b3}}^i$ .

In this paper the RPB is always for up-regulation (a decrease in electricity consumption). The model can also be used for modeling down-regulation, but this has not been confirmed to be realistic in the case site due to the long ramp-up time of the machinery.

The new production plan must satisfy all original constraints. The purpose of having the RPB in the beginning of the modeling period is to control the amount of time the model has to return the system to its original state. The model user can also choose to change the regulating hour. Similarly, in this work all regulating periods are one hour, but the model allows longer time periods to increase its adaptability to other analyses.

On the regulating hours, the amount of electricity production is unchanged, as combining production and consumption side bids is not allowed. The amount of electricity purchases is changed according to the accepted bid, but no cost or compensation is considered for the regulating power. Due to long lead times in starting up mechanical mass production machinery, it is asserted that to execute up-regulating bids, machines can only be turned off during the hours of the bid, and not started up to affect the net decrease in electricity consumption.

After the regulating hour(s), the mill site has either a surplus or deficit of mechanical mass compared to the original production plan. In case of up-regulation, the model needs to schedule additional production for hours after the regulating hours. To correct the mechanical mass deficit, the site is allowed to buy or sell additional electricity from or to the intra-day market. The amount and direction of trading is constrained in Equations (23) and (24) to prevent uncertain opportunistic trading that is untypical for a paper mill site and not in the focus of this work.

#### *Step 4: Calculation of the cost of regulation*

The difference between the total costs of operation in Steps 2 and 3 is calculated, and divided by the size of the RPB. This results in the cost caused by executing the RPB in €/MWh. Since no compensation or cost was assumed for the regulating power, this is the cost that needs to be compensated for the bid to be economically viable. In other words, it shows the minimum viable price of regulation.

#### *4.4. Elbas price estimation*

The intra-day prices were estimated from a set of realized Elbas trades at the case company. In contrast to e.g. Faria and Fleten [30], who use public data and a time series model for intra-day price modeling, a company-specific dataset from the year 2014 is used in this work.

For an industrial consumer in a producer dominant market, it is more realistic to model intra-day prices using a company-specific dataset than a general market dataset. For the large spot market the mill site is clearly a price taker, and we can thus simulate participation on that market based on realized prices. However, in the smaller Elbas market the prices are much more volatile and dependent on the time of purchase and the size of the bid (see the pricing mechanism in Section 2.2). In addition, market participants are very different in their motivations to participate in intra-day trading. For example, hydro power producers can use storage to optimize their production based on changing water values, and they have the option not to trade. In contrast, the case site typically has much less flexibility in whether or not to buy at a certain price, as it has a more specific need of electricity. This means that the case site often faces less favorable prices compared to most market participants. For these reasons, it is preferable to use data that describes how the company is actually succeeding on the market, rather than using general market data.

As shown in Equation (21), the intra-day prices for the model are divided into three price categories based on the assumption that buying higher volumes results, on average, in a higher purchase price due to demand-supply dynamics. Based on subjective estimates, it is assumed that under 20 MWh hourly volume is readily available in the Elbas market, and another 20 MWh could be achieved with reasonably good prices. If the hourly purchase exceeds 40 MWh, the purchase price should be relatively high.

Table 1 shows the estimated multipliers of intra-day prices (compared to day-ahead market) which are used in the model to forecast the intra-day prices. As an example, if the day-ahead (spot) price is 32 €/MWh, the model allows intra-day purchases up to 20 MWh/h for the price 32.32 €/MWh, additional purchases up to 20 MWh/h for 34.88 €/MWh, after which the price is 40.32 €/MWh. This pricing model captures the essential dynamics of the intra-day market and is based on actual trades, but it is noted that in reality, the possibilities to purchase power from Elbas vary significantly based on market conditions such as balancing needs and market tightness, and also based on individual asset conditions such as the hydrological situation on the main rivers in Finland.

Table 1: Day-ahead price multipliers for intra-day price for varying sizes of purchases.

Volume	0–20 MWh	20.1–40 MWh	40.1 MWh–
Multiplier	1.01	1.09	1.26

#### 4.5. Model statistics

A representative instance of the model has 6776 constraints and 5424 decision variables, 1100 of which are integer variables, including 1008 binary variables. Solving the model, written with AIMMS 4.13 and solved with CPLEX 12.6.2, takes about 5-8 seconds on a normal laptop. However, as is typical with mixed integer linear programming problems, some instances take noticeably longer to solve. Thus, an optimality gap of 0.1 % is used, along with a solve time limit of 30 seconds.

#### 4.6. Illustrative example

Price data for an exemplary modeling period is shown in Figure 3 with the intra-day prices for purchases of less than 40 MWh/h. With this and other inputs, like the fixed paper machine schedule, the model creates an optimal mechanical mass production schedule and power plant operating plan. The optimal production schedules of paper machines and mechanical mass production are shown in Figure 4 in gray and white.

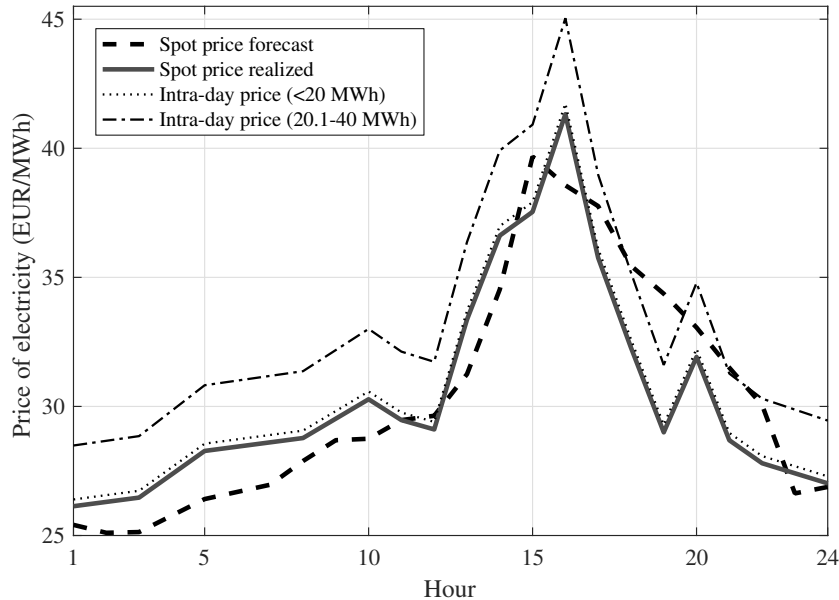


Figure 3: Price data for an exemplary model run.

The scheduled production of all production lines starts at the beginning of the period, continuing until the end with only the units with the lowest operating costs for each product type. This behavior is due to



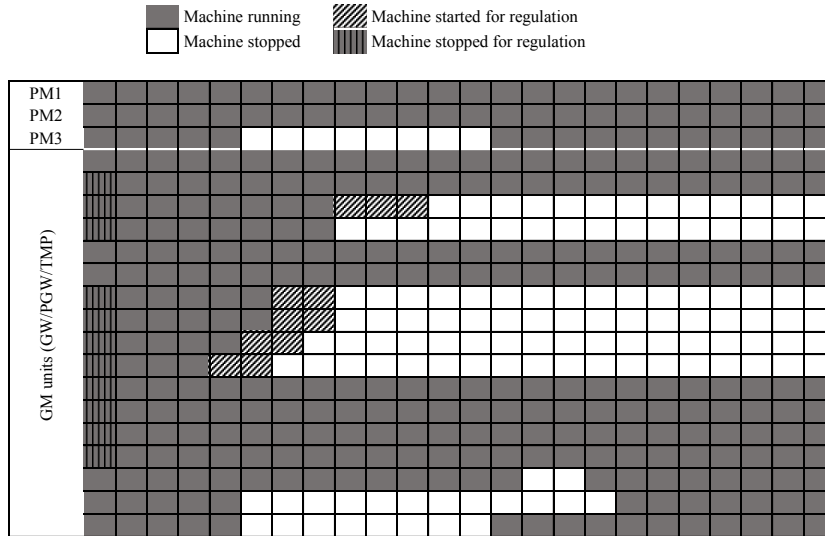


Figure 4: Illustration of the original and regulating scenario in an exemplary modeling period.

machines being running on hour 0 (no start-up costs on hour 1), and the forecast spot price also being low. Three lines are stopped mid-period, always either during the halt of PM3 or during the peak of the forecast spot price. It is notable that the schedules do not only follow the need of steam or the price of electricity, but a non-trivial combination of the two. Since the model does not constrain the starting or stopping of machines in any way, the shown schedule may not be recommendable in practice.

The cost of steam also depends on the forecast price of electricity through power plant operation. Figure 5 shows the operating points of the CHP plant in the modeling period. The fuel consumption of each extremal operating point is shown in megawatts next to the operating points. Electricity production is nearly constant outside a few peak hours, and heat production is altered. Heat production is also visualized in Figure 6.

The original production schedule is altered to execute an up-regulating power bid. In this case, the RPB is constrained to be approximately 20 MW, and the realized bid is also 20 MW. The realized bid size corresponds to the alteration with the smallest total cost increase. The realized alteration is shown in Figure 4. The consumption reduction for the RPB (shown with vertical stripes) is achieved through stopping 11 units in total. Production is compensated for later in the day (shown with diagonal stripes).

From the difference of the total costs of the original and altered schedule, the cost of regulation for the first hour can be calculated, in this case 95 €/MWh. Of this cost 58 % is caused by additional start-ups on hour 2, 33 % is caused by intra-day purchases and 9 % by increased fuel costs. Because the modeling period's average spot price is 30 €/MWh, the regulation price should be over 3 times the spot price to cover the costs for the mill site.

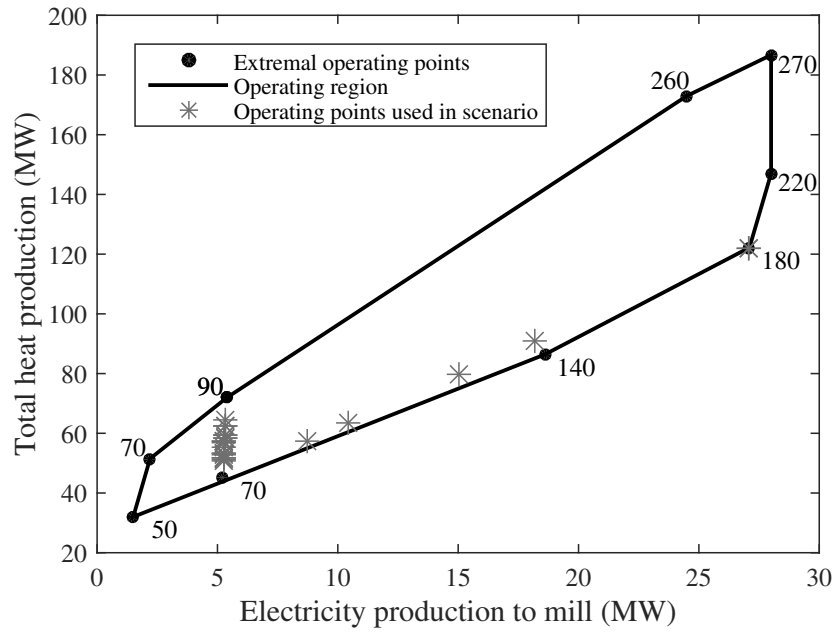


Figure 5: Power plant operating region and operating points during an exemplary model run. In numbers next to the operating points, the fuel power in each point is shown in megawatts.

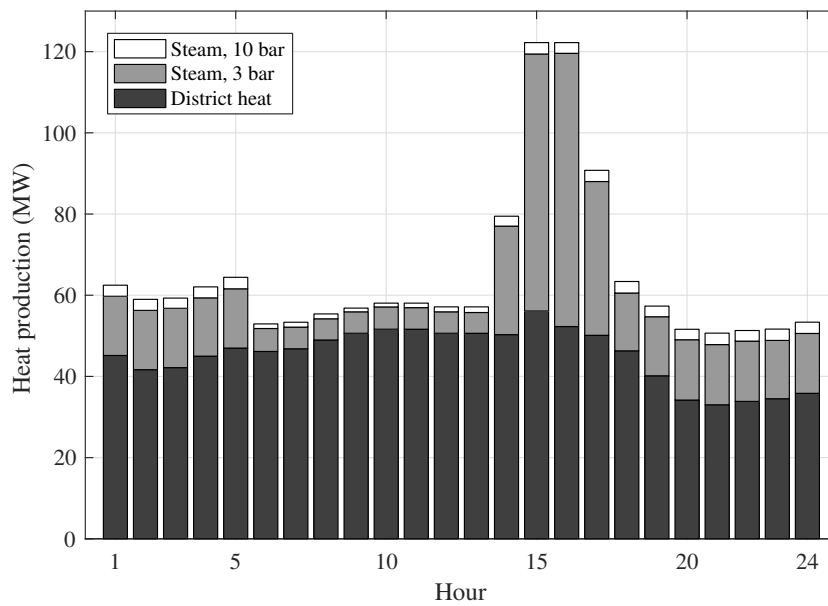


Figure 6: Heat production of the power plant during an exemplary model run.

## 5. Results

The aim of this section is to find out how much flexibility the modeled mill site can offer to the regulating power market and at what cost. The total electricity consumption of the mechanical mass production lines in the case mill site is around 100 MW. In the modelled scenarios this consumption is rarely achieved, so a lower 80 MW is used as the maximum up-regulating capacity of the mill site. In this section the cost of regulation relative to the spot price is estimated in different scenarios. Then, a stylized bidding curve is developed and tested against actual market conditions of 2014.

### 5.1. Cost of implemented regulating power bids

The cost of implementing RPBs of varying sizes is assessed by using the model described earlier. This is done by running a simulation for different 24-hour periods chosen from the year 2014. Specifically, these periods are sampled by selecting as the period starting point any hour where at least 80 MWh of up-regulation was actually sold in the regulating power market in Finland. This results in 611 different 24-hour periods that are known to be relevant from the regulating power perspective. For each of these periods, the model is used to calculate the costs of executing bids of 10,20,...,80 MW. Thus, in total, the model is run in  $611 \cdot 8 = 4888$  different situations and, out of these, it is possible to implement the bid in roughly 90 % of the cases. In the unsuccessful cases, especially large RPBs are impossible because of a technical reason, e.g. due to steam demand by paper machines and thus the inability to shut down TMP lines. From here on, only the successful runs are considered in the analysis.

The amount of implemented bids and the average cost of regulation for each bid size is listed in Table 2. The smaller RPBs are possible more often than the larger ones, which is expected due to reasons described above. The major factors that influence the cost of regulation are i) the volume of the bid, ii) the period's intra-day prices (determined by the spot price), and iii) the technical specifications of the mill, such as start-up costs and paper machine steam demand. The larger bids typically cost more to execute. Within a modeling period (for all bid sizes), parameters such as paper mill schedule and initial storage level are kept constant. The amounts of DH and sold steam are taken from historical realizations for the given period.

Table 2: Amount of possible bids and the average cost of executing regulating power bids.

Bid size (MW)	10	20	30	40	50	60	70	80
Implemented bids	604	601	570	583	566	560	541	384
Average cost (€/MWh)	59	63	65	61	62	64	67	69

The peak of the cost of regulation on 30 MW in Table 2 is due to a change in machinery used for the RPBs. One of the TMP lines can only be used for regulations of 40–80 MW due to its high electricity

consumption. The relatively low start-up cost of this line leads to a drop in the cost of regulation for bids of 40 MW or more.

The cost of regulation versus the average spot price for all runs with 60 MW of regulation is shown in Figure 7. The plotted lines illustrate where the cost of regulation is 1.5 and 2 times the average spot price. Close to 90 % of the realizations fit between these lines. On average, the technical cost per MWh of implementing a 60 MW up-regulating bid is 1.7 times the average spot price. The variance of the cost of regulation versus average spot price is strongly dependent on the bid size.

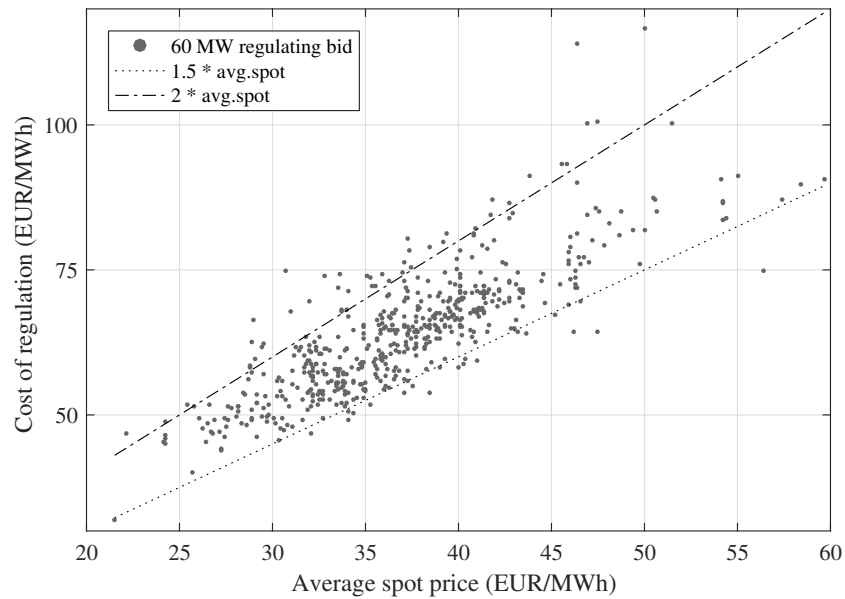


Figure 7: Cost of regulation versus average spot price shown for 60 MW regulating bids.

### 5.2. Flexibility cost curve

On the left hand side of Figure 8, the distribution of the flexibility cost ratio (regulation cost vs. average spot price) is shown for different amounts of regulation. The highlighted area around the median illustrates the 25% to 75% percentiles and the thin lines delimit approximately 99% of the values; the rest are considered outliers. Two phenomena can be observed: First, high regulation volumes cause higher unit costs than low volumes. This is explained by a higher need to purchase electricity from the intra-day market which, as explained in Section 4.4, exhibits prices that increase in demand. Also, it is not possible to allocate purchases to the cheapest hours only, due to many machine hours needed for additional production. With a low overall regulation volume, it is sometimes possible to make up for the regulation caused mass deficit without notable costs. With high volumes, however, the costs are inevitable and thus, even a risk seeking participant would need to bid with higher pricing.

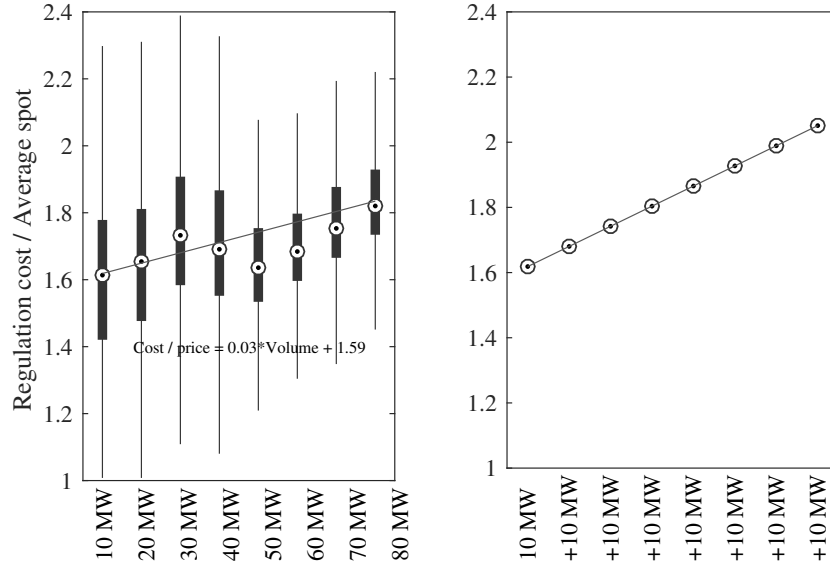


Figure 8: Left: The distribution of the ratio between regulation cost and average spot price for different sizes of activated regulating power bids. Right: The corresponding marginal cost curve used for bidding at breakeven price.

When this research was conducted, the minimum bid in the Finnish regulating power market was 10 MW. The bids have to be independent, which means that the case site cannot bid, e.g. 10 MW and 20 MW as alternative bids but needs to bid in 10 MW increments. This implies that the case site in question can, at maximum, offer eight different bids of 10 MW each and, assuming rational bidding behavior, it is also optimal to make the bids in 10 MW increments to mimic marginal cost based pricing as accurately as possible (because the marginal cost is not constant but increasing). Thus, the marginal cost curve on the right-hand side in Figure 8 is required for pricing each 10 MW bid. As an example, if the regulation cost for 10 MW is  $1.62 \cdot p_{\text{spot}}$  and for 20 MW  $1.65 \cdot p_{\text{spot}}$ , the first 10 MW should be priced at  $1.62 \cdot p_{\text{spot}}$  but the second 10 MW at  $2 \cdot 1.65 - 1.62 = 1.68 (\cdot p_{\text{spot}})$ .

Note that the marginal cost curve of Figure 8 represents the average marginal cost. In theory, the mill site could actually calculate the cost of regulation case by case using the optimization model. In the further examples, however, pricing based on the average case is assumed for better tractability and realism of the calculations. It is also realistic to assume that a paper mill would use a simplistic pricing equation rather than a complex optimization model.

### 5.3. Simulated activity for year 2014

The annual regulation potential of the case mill site is estimated by simulating its behavior in the 2014 Finnish regulating power market. The marginal cost curve of Figure 8 is used as a basis for pricing and the volumes sold to the market are calculated based on realized up-regulation volumes and prices. Specifically,

it is assumed that the site can freely participate on any number of regulating hours and the realized bid is calculated for each hour as follows: the accepted bid is the largest possible of the 10...80 MW bids where both actual regulation price and volume exceed the corresponding bid price and volume. Throughout the analysis, it is assumed that the site is a price-taker and can capture any share of the market without a price impact.

There were in total 2088 hours of up-regulation in Finland in 2014 and the market total volume adds up to 137.8 GWh. In the simulation, the case site would have captured 12.8 GWh of the market by participating on 254 hours with an average of 50 MW. The corresponding market share would have been 9.3 %.

The frequencies of accepted bid sizes are shown on the left-hand side of Figure 9. By far the most often accepted bid size would have been 80 MW. The mill site's market share of the regulating power market during the hours of the accepted bids is shown on the right-hand side of Figure 9. It is notable that the median market share during these hours is 50 %, indicating that this site alone could account for half of the regulation needs in Finland when market conditions permit participation. This is affected by the frequently accepted 80 MW RPB shown on the left-hand side.

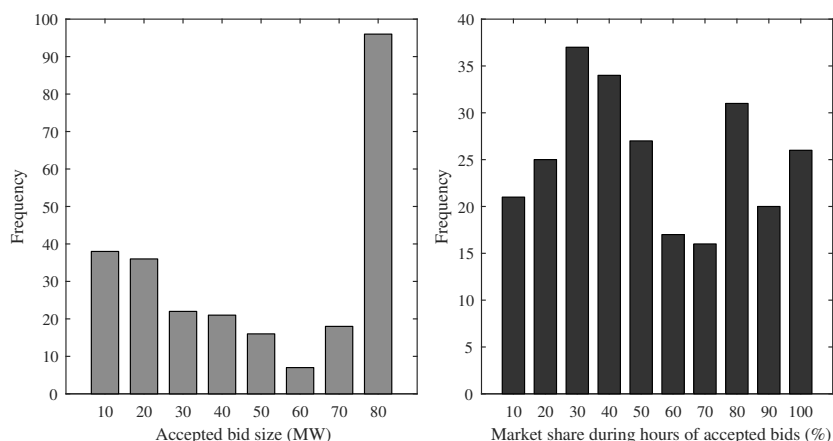


Figure 9: Left: Frequencies of accepted regulating power bid sizes in simulation. Right: Simulated market share of the mill site in the regulating power market during regulating hours.

#### 5.4. Risk consideration

The prices calculated above are based on technical costs when all processes work as expected. In reality, the mill site must account for risks when pricing regulation: First, the utilization of mass tower flexibility introduces a production risk for the site's end product, paper. Both GW and TMP lines suffer from unreliable start-ups and whenever they are shut down for up-regulation, there is a moderate chance of a significant ramp-up delay after the regulation is over. Besides the obvious imbalance cost risk, this can also lead to severe mass deficits which can result in a paper machine shut-down. In addition to a large technical

cost of ramping a paper machine down (and up), production halts may lead to late deliveries due to tight production and logistics schedules. These carry very high costs in the form of price reductions and loss of customer satisfaction. Second, if large up-regulation actions are expected, re-starting multiple lines after the regulation can require extra resources (operators) that carry a cost. Third, other potential sources for added costs relate to quality problems due to process disruptions, needs to use expensive fuels such as oil at the power plant to satisfy steam demand, and the general operational risk posed by conducting market operations in an environment that is designed for running an industrial production process.

The estimation and/or modeling of these risks is rather complex and outside of scope for the presented model. In addition, statistical estimation of disruption probabilities is generally unreliable in many cases and here, the case company did not share such data due to confidentiality issues. However, based on anecdotal evidence, a stylized sensitivity analysis of the risk premium will be presented, i.e. a price add-on that the mill site would need to add to their cost to cover risks. For context, a survey regarding the costs of downtime in Swedish manufacturing companies is presented in [31].

For risk consideration, the following assumptions are made: A disruption in mass production carries a cost of 1000 €, and a consequent major disruption in paper production costs 500 k€. Note that the latter can only occur after a mass production disruption, as in the model the paper machines do not participate in the regulation market. Additionally, it is assumed that the probability of a paper machine disruption does not depend on the volume of regulation, but the probability of a mass production disruption grows linearly with each additional 10 MW of up-regulation. By varying the probabilities of these regulation bid initiated disruptions, an expected value for the delay cost of one regulation event can be calculated.

In Table 3, a collection of probabilities are presented for the failure in mass production and a subsequent failure in paper production, and the corresponding risk premium dictated by the expected cost of disruption. Moreover, corresponding results are shown to earlier analysis of the total market participation in 2014, but with different risk premiums added to the bid price for up-regulation market.

Table 3: Simulated up-regulation volumes for the case site in 2014 with varying disruption probabilities.

Pr(mass prod. disruption)	0 %	5 %	10 %	15 %	5 %	10 %	15 %
Pr(paper machine disruption)	0 %	5 %	5 %	5 %	15 %	15 %	15 %
Risk premium (€/MWh)	0	30	60	90	80	160	240
Implemented bids (GWh)	12.8	6.5	4.2	3.4	3.4	1.2	0.2
Implemented bids (qty)	254	99	63	45	47	24	4
Market share	9.3 %	4.7 %	3.1 %	2.4 %	2.5 %	0.9 %	0.2 %

It can be observed that the volume of accepted bids drops even with relatively small risk premiums and, depending on the assumed error proneness of the production lines, the market share decreases from

relatively large to minimal.

## 6. Discussion

The results in this paper highlight the economic viewpoint in the assessment of the potential of a large paper mill site to participate in the regulating power market. From a technical perspective, the site can offer 80 MW of regulation capacity for most hours of the year. Because the site accounts for some 20 % of all mechanical pulp production in Finland, the total potential of the industry (assuming identical production sites) is some 400 MW. This is a vast capacity, as the average need for up-regulation activations in Finland was only 16 MWh/h (includes all hours) in 2014. When the site's participation in the market was simulated with the presented pricing model, its average hourly participation was 1.4 MWh/h, which would correspond to 7.3 MWh/h on industry level. This would translate into a remarkable 37 % share of the whole up-regulation market (under the assumption that everyone would operate as price takers with identical bidding curves). Gils [15] estimated that the pulp industry accounts for around 70 % of demand response capacity potential in Finland.

The above figures represent maximum breakeven potentials without the consideration of risk or profit premiums. It was noted in Table 3 that the share of accepted bids drops quite quickly if a risk premium is added to the marginal cost. Indeed, based on input from the case company, the simulated market share without risk considerations is significantly higher than the site's realized participation. The main reason is the difference between the actual bidding curves and the one presented in this work. There are multiple factors embedded in the actual bidding behavior that are not captured by the technical model of the site, the most important being the imposed risk for the main production process. The results, considered with roughly estimated risk premiums, suggest that the total market share of mechanical pulping in Finland could settle somewhere between 10 % and 20 %.

The findings of this work are partially comparable to Paulus and Borggreffe [6], who evaluate the potential of mechanical pulp production in the German regulation market. They assess that the industry's total running capacity is 312 MW and average volume of pulp storage is 1.5 hours, ending up modeling the industry as an energy storage with some 500 MWh of storage capacity. In their market simulation for year 2020, they however found that virtually no energy was sold as up-regulation to the market (0 % calls for positive capacity) by pulp producers. This result is somewhat surprising, given that their estimate for variable cost of participation was estimated to be  $\leq 10$  €, when the estimate in this work is linked to the spot price by a multiplier ranging from 1.5 to 2, which certainly results to a higher cost estimate. In any case, Paulus and Borggreffe [6] conclude that IDSM has potential to provide some 50 % of the regulation capacity in the future, but this is not generally used as balancing power due to high costs of load reduction. This study (from the Nordic market) paints a similar picture, even though it shows some potential for actual



participation, too.

The focus of this paper is in the economic feasibility of IDSM from an industrial player's point of view. As discussed by Gils [15], in countries with energy intensive industries, the IDSM capacity potential is significant: there are many industrial processes that can, on technical terms, be ramped down in 15 minutes, which is the current requirement for tertiary reserves. It is a totally different question, however, how an industrial company bids that capacity to the market. This study focused on Finland, where the TSO runs a clearing price auction mechanism to acquire regulating power. In this setting, the capacity becomes available in merit order. The results suggest that the IDSM of mechanical pulping, which has perhaps most potential across all industries, i) has an increasing marginal cost due to process complexity and ii) requires a high risk premium mainly due to stability requirements of paper production. Due to these reasons, it is very likely that the DSM potential of these sites can be harnessed only partially.

## 7. Conclusions

This paper describes a model for assessing the realized costs of up-regulating power bid execution (consumption decrease) with mechanical mass production machinery in a pulp and paper mill site. These costs stem from the requirement to make up for the pulp deficit caused by the regulation in the following 23 hours, which may require additional start-ups and costly intra-day purchases. The baseline for calculations is an optimized production plan against a fixed paper production schedule. Comparing this optimized plan with the post-optimized one (including regulation) allows the calculation of the cost of regulation. The model is then used to calculate a marginal cost curve for each additional 10 MW consumption decrease, which can be used as a basis for pricing up-regulating bids. In the case site, this resulted in bidding with approximately 1.6–2 times the day's average spot price. This pricing model was tested against 2014 market data and it was found that the potential of the site can be turned into significant amounts of regulating power.

These results suggest that IDSM can play a major role in the regulation markets, at least in countries with energy intensive industries. In theory, there is ample IDSM capacity available. However, for most of this capacity, the rational bidding price is relatively high, meaning significantly higher than the underlying spot price. In addition to the technical cost calculated in this paper, significant risk premiums need to be added to this price due to sensitivity of the paper making process and other factors. This limits the expected usability of the large potential capacity in mechanical pulping, or at least makes it very expensive for the TSO to fully activate it. The authors believe that this result is partially applicable to other industries and countries, too. In this light, further actions are encouraged to activate potentially more cost-efficient technologies for demand side management, such as residential water boilers, and other means of flexibility, such as utilization of heat producing units and heat storages. In general, policy makers and other decision makers should focus on the economical aspects when comparing technologies that offer flexibility. Otherwise

counterbalancing the increase of renewable energy might lead to cost inefficient energy systems.

The model presented in this paper offers insight into the industrial viewpoint of flexibility of electricity consumption. It is not, however, fully comparable to the real market behavior due to exclusion of, e.g. risks and the impact of intra-day price forecast errors. The model could be expanded in the future by including the optimization of paper production schedules, which would both provide additional DSM potential and an analytic way to assess the production disruption risk. This, and the inclusion of intra-day price uncertainty modeling, would make a case for stochastic optimization formulation. In assessment of the site's potential to participate in the regulating power market, the current approach of capturing each feasible opportunity as a price taker in a historical market situation does not fully describe the actual potential in the future; instead, a regulation market simulator could be used to gain better insight. Finally, as a case study, the current work could be expanded by assessing other pulp mills, other industrial sites, and other regulation markets to validate the generalizability of the results.

## **Acknowledgements**

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## **Nomenclature**

### *Abbreviations*

CHP	Combined heat and power
DH	District heat
DSM	Demand side management
GM	Grinding machine
GW	Groundwood
IDSMS	Industrial demand side management
PGW	Pressurized groundwood
RPB	Regulating power bid
TMP	Thermomechanical pulp
TSO	Transmission system operator

### Parameters

$A_{GW}$	A large positive integer, auxiliary parameter for GW scheduling
$DH_{req}^i$	District heat requirement on hour $i$ (MWh/h)
$E_{cons}^j$	Electricity consumed by application $j$ (MWh/h)
$E_{price}^i$	Price of electricity (€/MWh)
$E_{pur,noreg}$	Electricity purchases in Steps 1 and 2 (MWh)
$GW_{stones,min}^{l,GW}$	Minimum number of running stones in GW line
$K_{CHP}^{k,Dc}$	Operating point ( $k$ ) data for the power plant
$M_{cons}^j$	Mechanical mass consumed by application $j$ (adt)
$M_{delay}^s$	Amount of time steps a unit of mass must remain in tower $s$ (integer)
$M_{prod}^j$	Mechanical mass produced by application $j$ (adt)
$M_{rec}^{u_1,u_2}$	Parameter controlling mass processing
$Rec^{j,u}$	Parameter for machine-tower connections
$Reg_{dir}$	Binary parameter denoting the direction of regulation
$Reg_{scen}$	Binary parameter, 1 on the Step 3, 0 otherwise
$S_{cons,10bar}^j$	Amount of 10 bar steam consumed by application $j$ (MWh/h)
$S_{cons,2bar}^j$	Amount of 2 bar steam consumed by application $j$ (MWh/h)
$S_{cons,3bar}^j$	Amount of 3 bar steam consumed by application $j$ (MWh/h)
$S_{gen,2bar}^j$	Amount of 2 bar steam generated by application $j$ (MWh/h)
$S_{incrProd,cost}$	The cost of increased production of heat in power plant (€/MWh)
$S_{price,3bar}$	Price of purchased 3 bar steam (€/MWh)
$S_{sold,3bar}^i$	Amount of steam sold (MWh/h)
$S_{pur,ch,max}$	Maximum hourly change of 3 bar steam purchases (MWh/h)
$S_{pur,max}$	Maximum purchase of 3 bar steam (MWh/h)
$T_{step}$	Timestep length (hours)

### Variables

$\lambda_{\text{CHP}}^{k,i}$	Turbine convex combination weight factor for point $k$
$\text{CHP}^{Dc,i}$	Operating point of the power plant (fuel, electricity, total heat) (MWh/h)
$DH_{\text{cooling}}^i$	Amount of additional cooling of DH water (MWh/h)
$E_{\text{pur,id,b}}^i$	Amount of intra-day purchases in blocks (b1,b2,b3) (MWh/h)
$E_{\text{price,id}}^i$	Price of intra-day electricity in blocks (price1,price2,price3) (MWh/h)
$E_{\text{rev,id}}^i$	Income or cost from intra-day trading of electricity (€/h)
$E_{\text{pur,id,total}}^i$	Total Intra-day electricity purchase (MWh/h)
$E_{\text{pur}}^i$	Electricity purchased/sold (MWh/h)
$E_{\text{reg,vol}}$	Time-invariant amount of regulation (MWh/h)
$F_{\text{cost}}^i$	Cost of consumed fuel (€/h)
$GW_{\text{active}}^{i,l\text{GW}}$	Binary variable denoting that a GW line is running
$GW_{\text{stonesON}}^{i,l\text{GW}}$	Number of stones that are running
$M_{\text{move}}^{i,u_1 \rightarrow u_2}$	Mass moved between storages (adt/hour)
$M_{\text{stor,init}}^u$	Initial storage of mass in storage tower $u$ (adt)
$M_{\text{stor,ready}}^{u,i}$	Mechanical mass ready for next processing step (adt)
$M_{\text{stor,total}}^{u,i}$	Mechanical mass in storage tower $u$ (adt)
$E_{\text{spot}}^i$	Costs from the spot trade (€/h)
$Q_{\text{prod}}^{Dq,i}$	Production of heat components in the power plant (MWh/h)
$R_{\text{DH}}, R_{\text{M}}, R_{\text{S}}$	Penalty costs for DH, mass, and steam processes (€)
$S_{\text{incrProd}}^i$	Amount of increased heat production in power plant (MWh/h)
$S_{\text{pur,3bar}}^i$	Amount of purchased 3 bar steam (MWh/h)
$S_{\text{red,10bar}}^i$	Amount of 10 bar steam lowered to 3 bar level (MWh/h)
$S_{\text{red,3bar}}^i$	Amount of 3 bar steam lowered to 2.5 bar level (MWh/h)
$S_{\text{vent,10bar}}^i$	Steam (10 bar) vented into outside air (MWh/h)
$S_{\text{vent,2bar}}^i$	Steam (2 bar) vented into outside air (MWh/h)
$S_{\text{vent,3bar}}^i$	Steam (3 bar) vented into outside air (MWh/h)
$Y^{j,i}$	Application $j$ state ON/OFF (binary)

### *Sets*

$Dc, Dc_{set}$	Power component of CHP production, set of all components (elec, fuel, heat)
$Dq, Dq_{set}$	Heat component of CHP production, set of all components (10bar, 3bar, DH)
$i, i_1, i_2, T, T_{set}$	Current timestep ( $i_x$ ), highest timestep of calculation, set of timesteps (integer)
$j, J$	Machine, set of all machines
$k, K_{op}$	Power plant operating point, set of all points
$l_{GW}, l_{GW, set}$	GW line, set of all GW lines
$Reg_{hrs} \subset T_{set}$	Set of timesteps for which regulating power bid is accepted
$u_1, u_2, u_3, U$	Storage tower ( $u_x$ ), set of towers

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