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The chemical pulp mill as a flexible prosumer of electricity

Simon Ingvarsson *, Mikael Odenberger, Filip Johnsson

Department of Space, Earth, and Environment, Chalmers University of Technology, 41296 Gothenburg, Sweden

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ABSTRACT

Chemical pulp mills act as industrial-scale prosumers of energy, in that they demand heat and electricity for the production processes while supplying heat and electricity from the combustion of by-products. As such, they have potential relevance as providers of flexibility to the electricity system, supporting the integration of variable renewable electricity generation.

In this study, a novel dispatch optimisation model is presented and applied to a generic mill, covering the production processes, boilers, and turbines, together with the associated storage of intermediate products. We analyse the trade in electricity between the mill and the central grid, the economic value of pulp mill flexibility, and the internal dynamics of the mill, when flexibility measures in different parts of the mill are combined.

The results show that the suggested flexibility measures increase the amount of sold electricity during high-value hours and reduce the amount of sold electricity during low-value hours. In the present electricity market, the value of the electricity traded with the central grid is, thereby, increased by 1–8% compared to steady-state operation, without impacting the pulp production volume. The results reveal both synergies and conflicts between the different flexibility measures, underlining the importance of mill-wide optimisation.

1. Introduction

The share of global electricity supply generated by variable renewable electricity sources, such as wind and solar power, has increased over the last decades and is expected to continue increasing, following the reduced costs of these technologies and policy incentives aiming for energy security and climate change mitigation [1].

This development implies a transition from the historical system dominated by dispatchable generation and variations primarily on the demand side to a new setting with variations also on the supply side and highly variable electricity prices. Cost-efficient integration of variable renewable electricity requires the implementation of flexibility measures that can reduce the price variations by shifting, absorbing or complementing the electricity load [2]. Depending on the duration, frequency and amplitude of the variations, various flexibility measures are viable, including supply control, industry and household demand-side management, battery storage, and increased integration with the heating sector [3]. Depending on the time-scale, these measures can be activated by arbitraging electricity on the spot market or by participation in specific markets for flexibility.

Chemical pulp mills are interesting actors in the future electricity system because they can provide several of these flexibility measures. The mills are relatively large consumers of both heat and electricity in their production processes, although they also supply heat and electricity from the excess steam that is generated from the combustion of by-products. In this way, they act as industrial-scale prosumers of energy.

The pulp and paper sector is one of the largest industrial sectors in terms of energy consumption in the European Union [4], as well as in the United States, China and India [5]. In Sweden, the pulp and paper industry accounts for over 50% of the total industrial energy demand, using 72 TWh of energy annually, of which 52 TWh is biomass (mainly from the production side-streams), 2 TWh is fossil fuels, and 18 TWh is electricity [6]. Around 6 TWh/year of electriciy is produced internally in the chemical pulp mills [7]. Due to the high share of biogenic feedstock, the pulp and paper industry is a small net-emitter of carbon dioxide, and the main focus areas of research and development within this sector has traditionally been on efficiency measures and increased value of side-stream products.

For a systematic review of flexibility measures at a pulp mill, categorisation of these measures is introduced here (cf. work by Beiron et al. [8] on combined heat and power plants). The types of flexibility measures are:

* Corresponding author.
E-mail address: simon.ingvarsson@chalmers.se (S. Ingvarsson).

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- Steam supply flexibility, whereby the total steam supply for process steam demands and electricity generation is varied, using over-capacity in the boilers and storage of fuels.
- Steam demand flexibility, whereby the available steam is prioritised for either the process steam demands or electricity generation. This is achieved by varying the level of steam consumption, using over-capacity in the steam-demanding processes and storage of intermediate products. Depending on the configuration, this changes the share of steam directed to turbines and pressure-reducing valves (PRVs) respectively, or the utilisation of different turbine types.
- Steam storage, whereby energy is stored as steam in accumulators and used to decouple the steam supply from the steam demand.
- Electricity demand flexibility, whereby electricity consumption is directly varied, using the over-capacity in electricity-demanding processes and storage of intermediate products.
- Product flexibility, whereby the energy supply and/or demand is varied by alternating between different raw materials (e.g., virgin vs. recycled materials) or end-products (e.g., softwood pulp vs. hardwood pulp or market pulp vs. paper for an integrated mill).

Flexible operation of pulp mills has been examined in several previous studies. Sarimveis et al. [9] applied a dispatch optimisation model with hourly resolution to study steam supply flexibility and the ways in which exogenous variations in steam demand can be met by varying the steam flows between back-pressure turbines and PRVs. Their results show that this method can be a very useful tool for operational decision support to reduce fuel and electricity costs. Marschman et al. [10] used a similar approach, in which a condensing turbine was also included in the model for increased electricity production potential. They found considerable value associated with flexible operation in several case studies. Karlsson et al. [11] modelled a full year with monthly resolution and varying fuel prices. Their results show that system costs can be lowered by implementing steam supply flexibility on a seasonal time-scale, achieved by long-term storage of fuels. Xu et al. [12] studied steam supply flexibility and thermal storage on sub-hourly time-scales, to assess the chemical mill's ability to provide ancillary services to the power grid.

Steam demand flexibility was studied from an investment decision perspective by Cakembergh-Mas et al. [13]. They used an optimisation model with monthly resolution to compare retrofit investments in different configurations of back-pressure and condensing turbines, in combination with measures to reduce process steam demands. Trojan et al. [14] showed (for a thermal power plant) how flexible feed-water heating, through the control of the low-pressure bleed from a back-pressure turbine and hot-water storage in the feed water to the plant can shift power production from low-value to high-value hours.

Panuschka and Hofmann [15] studied the impact of thermal flexibility in industrial energy supply systems by assessing how adding a Ruth's type accumulator affects the operational costs of a representative Austrian pulp and paper mill. They found that this could reduce costs by smoothing out minor variations in the steam demand.

With respect to electricity demand flexibility, several studies have looked at thermo-mechanical pulp (TMP) mills, which consume large amounts of electricity in their refining processes [16–19]. Less research has been carried out on the electricity demand flexibility of chemical pulp mills, although a cost optimisation study of flexible operation of a single production step (the wood chopper) was performed by Uuemaa et al. [20].

A special kind of product flexibility in chemical mills was studied by Svensson et al. [21,22], who included lignin separation in their model, as an alternative use for the black liquor, which would otherwise be combusted in the recovery boiler to produce steam for electricity generation. Product flexibility for TMP mills was studied by Shoepf et al. [23].

Lastly, a brief survey of flexibility from the mill-wide perspective was conducted by Jannasch et al. [24]. They also discuss the inter-dependencies of flexibility measures in different parts of the mill. Steam demand flexibility in production processes is limited by the capacities of boilers and turbines. In the other direction, steam supply flexibility depend entirely on the demand-side processes because the steam boilers are commonly fuelled by bark and black liquor, which are generated as by-products from the demand-side processes. In the survey, costs and limitations for the various types of flexibility were quantified, although an in-depth analysis of the dynamics was not made.

In summary, steam supply flexibility and steam storage have been addressed from various perspectives and on different time-scales, ranging from sub-hourly to seasonal. The novelty of the present work is that it jointly addresses flexibility in steam supply, steam demand, electricity demand and in product. This enables the analysis of the dynamics in the mill when several flexibility measures are combined, and of the inter-dependencies between flexibility measures on the hourly and seasonal time-scales.

In this study, a novel dispatch optimisation model with hourly resolution is presented and applied to a generic chemical pulp mill over a time period of 1 year. The mill's dynamic integration with the electricity market is analysed in order to answer the following questions:

- How is the interplay between the mill and the electricity market altered when material and energy flows within the mill are jointly optimised in response to price signals?
- How are the internal dynamics of the mill between the boilers, turbines and production processes affected by flexible operation?
- What is the economic value of flexible operation and how is this value affected by synergies or trade-offs between different flexibility measures?

2. Method

In this work, a reference chemical pulp mill, which is a stand-alone mill with a daily capacity of 2,000 ADt (air-dry tonnes) of bleached market pulp, is modelled. It can be operated either exclusively with softwood (spruce or pine) or in campaign mode, whereby the mill switches between periods (campaigns) of softwood pulp production and periods of hardwood (birch) pulp production. A fraction of the softwood input is supplied as wood chips from a sawmill that is assumed to be located nearby. The model is based on the steady-state description in Åforsk Model Mills 2010 [25], representing the best-available technology at the time of its publication. Discrepancies between the Åforsk Model mill and the current Swedish mills are discussed in the Åforsk report, and a comparison with Finnish mills has been covered by Kangas [26].

A sketch of the mass and energy balances of the modelled pulp mill and the links to its surroundings are presented in Fig. 1. Three energy carriers are included: electricity, steam, and materials/fuels. Conversion from fuels to steam takes place in a recovery boiler that combusts the black liquor and in a separate bark boiler. Electricity is produced by two generators, which are connected to one back-pressure turbine and one condensing turbine, respectively. The generated electricity and steam are supplied to industrial processes throughout the mill, such that the mill is self-sufficient in terms of heat and a net-exporter of electricity. The lime kiln is fuelled by gasified bark (as is the case for several mills currently operating in Finland, Brazil, China and Indonesia [27]), such that no externally supplied fuels are needed.

2.1. Optimisation model

The reference mill is modelled with a linear optimisation model with hourly resolution. The model nomenclature is defined in Table 1. The optimisation objective is to minimise the total cost of operation C over the modelled time period, by varying the material, steam and electricity flows throughout the mill, while maintaining all the energy and mass balances within the system.

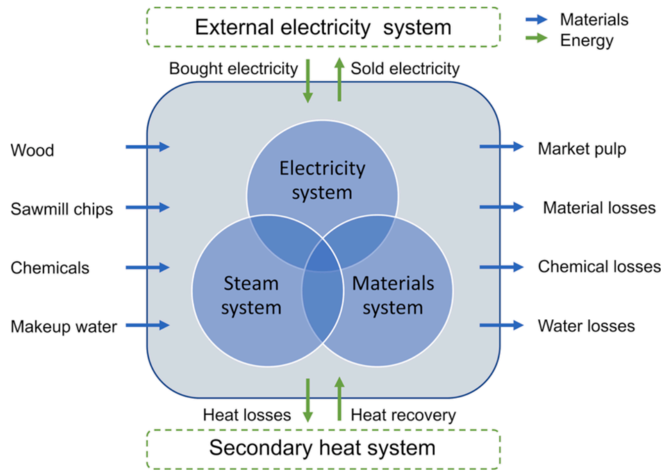


Fig. 1. Visual representation of the studied system (filled rectangle) and subsystems (interconnected circles), with arrows representing the exchanges of mass and energy with the surroundings.

Eq. 1 gives the objective function for softwood-only operation, where $E^{use}_{p,t}$ is the electricity consumed in each process p at each time t and $E^{gen}_{\theta,t}$ is the electricity generated by each turbine θ. External supplies, $M^{ext}_{p,t}$ and W^{ext}_t, are allowed for wood, white liquor chemicals, lime and make-up water. All costs c^{el}_t, c^{ext} and c^w are given exogenously.

$$min\ C = \sum_T \left[c^{el}_t \left(\sum_P E^{use}_{p,t} - \sum_\Theta E^{gen}_{\theta,t} \right) + \sum_P c^{ext}_p M^{ext}_{p,t} + c^w W^{ext}_t \right] \tag{1}$$

The aggregated demand D for the end-product (market pulp) is fixed over the total time period, such that $\sum_T M^{out}_{PD,t} \geqslant D$, where $M^{out}_{PD,t}$ is the hourly output from the pulp dryer.

An overview of the material flows throughout processes and boilers is presented in Fig. 2. The mass balances over each process are maintained, connecting the output $M^{out}_{PD,t}$ to the input $M^{in}_{p,t}$, according to:

$$M^{out}_{p,t} \leqslant a_p M^{in}_{p,t-d_p} \qquad \forall p \in P, \forall t \in T \tag{2}$$

where a_p is a fixed quota accounting for material losses and unit conversions and d_p is the time duration of the process. Furthermore, the operation of each process at each time-step is limited by the maximum and minimum loads, such that $m^{min}_p \leqslant M^{in}_{p,t} \leqslant m^{cap}_p$.

The processes are grouped into three process chains $P_k, k = 1, 2, 3$, corresponding to the pulp production line, the recovery cycle and the lime cycle, as shown in Fig. 2. Material flows between the different processes are kept balanced, making use of intermediate storage units where available, according to Eq. 3, where $p - 1$ is the upstream process adjacent to p within the same process chain. For processes that form linkages between the process chains (digester and causticiser), there is a fixed ratio between the two different inputs. Storage levels $M^s_{p,t}$ are limited by an upper limit $m^{s,max}_p$ for each product at each time-step, such that $M^s_{p,t} \leqslant m^{s,max}_p$. A separate balance is maintained for bark, which is used in both the bark boiler and as fuel for the lime kiln, according to Eq. 4, where subscript WY represents the wood yard, BB is the bark boiler, and M^{kiln}_t is the bark used as fuel in the lime kiln. The marginal value of this equation can be interpreted as the internal value of the bark within the studied system.

$$M^s_{p,t} \leqslant M^s_{p,t-1} + M^{out}_{p-1,t} - M^{in}_{p,t} + M^{ext}_{p,t} \quad \forall p \in P_k, \forall t \in T \tag{3}$$

$$M^s_{bark,t} \leqslant M^s_{bark,t-1} + \left(M^{in}_{WY,t} - M^{out}_{WY,t} \right) - M^{in}_{BB,t} - M^{kiln}_t \quad \forall t \in T \tag{4}$$

An overview of the steam system is presented in Fig. 3. Four steam pressure levels (HP, MP2, MP, and LP in Fig. 3) and condensate returns at four different temperature levels are included in the model. The mass balances of the steam and condensate (and the corresponding energy balances) are maintained for each temperature/pressure level l, according to Eq. 5, where $S^{gen}_{l,p,t}$ and $S^{use}_{l,p,t}$ is the mass of steam generated or used by each process connected to the specific level. $S^{dir}_{l,t}$ is the steam flow to the nearest-below pressure level. For the LP steam and condensate levels, $S^{dir}_{l,t}$ is directed to the feedwater tank.

Table 1
Model nomenclature. Parameters are also known as exogenous variables.

SETS

Symbol	Index	Description
L	l	pressure/temp. levels
P	p	processes
T	t	time (hours)
Θ	θ	turbines

VARIABLES

Symbol	Unit	Description
$E^{gen}_{\theta,t}$	MWh/h	electricity production by turbine
$E^{use}_{p,t}$	MWh/h	electricity consumption by process
M^{kiln}_t	t/h	bark to lime kiln
$M^{ext}_{p,t}$	t/h	external supply of input material
$M^{in}_{p,t}$	t/h	process material input
$M^{out}_{p,t}$	t/h	process material output
$M^s_{p,t}$	t	material storage level
Q^{sec}_t	MWh/h	secondary heat supply
$S^{dir}_{l,t}$	t/h	steam throttle to below level
$S^{ext}_{l,t,\theta}$	t/h	exhaust steam flow by turbine stage
$S^{in}_{l,t,\theta}$	t/h	inlet steam flow by turbine stage
$S^{gen}_{l,p,t}$	t/h	generated steam/water by process
$S^{use}_{l,p,t}$	t/h	consumed steam/water by process
W^{ext}_t	t/h	make-up water to feed-water system
W^s_t	t	feed-water storage level

PARAMETERS

Symbol	Unit	Description
a_p	–	input/output conversion factor
b_p	–	secondary/primary input mass ratio
c^{el}_t	€/MWh	cost of electricity
$c^{ext}_{p,t}$	€/t	cost of wood, NaOH and CaO
c^w	€/t	cost of make-up water
h_l	MWh/t	enthalpy of steam/water
m^{cap}_p	t	max. capacity of process
m^{min}_p	t	lower limit of process operation
$m^{s,max}_p$	t	max. storage limit for processes
$m^{w,max}_p$	t	max. storage limit for feed water
$s^{use}_{l,p}$	–	steam/water used per material
$s^{gen}_{l,p}$	–	steam/water generated per material
$s^{in,max}_\theta$	t/h	max. turbine inlet
$s^{in,min}_\theta$	t/h	min. turbine inlet
$s^{ext,max}_\theta$	t/h	max. turbine (stage) exhaust
$\alpha_{l,\theta}$	MW/t	linear turbine model coefficient
β_θ	MW	linear turbine model offset
η^{gen}	–	generator efficiency
τ_p	h	process duration

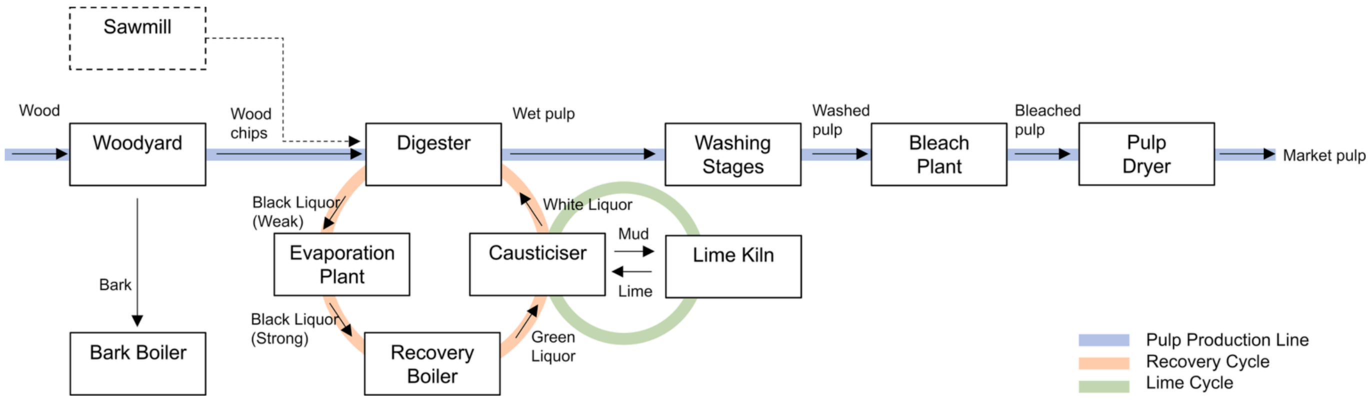


Fig. 2. Schematic of the product flows and intermediate storage units throughout the mill. The processes are grouped into three process chains, highlighted with blue, orange and green colours. In addition to what is shown, fractions of the white liquor and lime are supplied externally to make up for losses during each cycle.

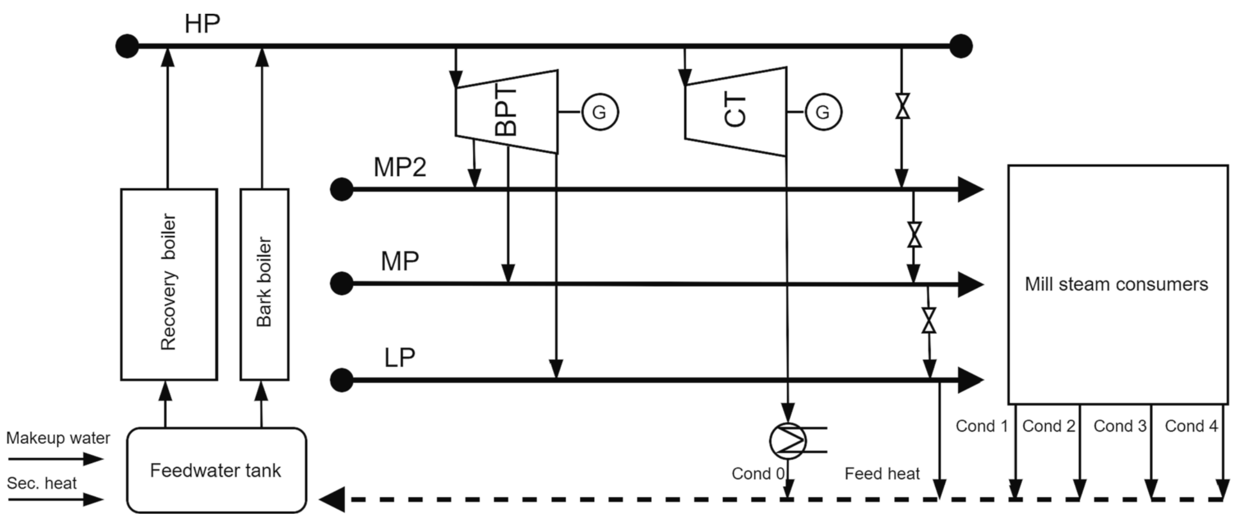


Fig. 3. Schematic of the type mill's steam system. Mill steam consumers correspond to the boxes in Fig. 2, including the boilers' internal demands for pre-/inter-heating and soot blowing.

$$\sum_{P}\left[S^{gen}_{l,p,t}-S^{use}_{l,p,t}\right]+\sum_{\Theta}\left[S^{ext}_{l,t,\theta}-S^{in}_{l,t,\theta}\right]+S^{dir}_{l',t}-S^{dir}_{l,t}\geqslant 0 \quad \forall l\in L,\forall t\in T \tag{5}$$

The levels of instant steam, condensate and electricity generation and usage in each process are proportional to the total mass of material in the process during that time-step. See Eqs. (6)–(8). To account for all the material being processed, the inputs are summed over a duration cycle.

$$S^{use}_{l,p,t}\geqslant\frac{s^{use}_{l,p}}{\tau_p+1}\sum_{t'=t-\tau}^{t}M^{in}_{p,t'} \quad \forall l\in L,\forall p\in P,\forall t\in T \tag{6}$$

$$S^{gen}_{l,p,t}\leqslant\frac{s^{gen}_{l,p}}{\tau_p+1}\sum_{t'=t-\tau}^{t}M^{in}_{p,t'} \quad \forall l\in L,\forall p\in P,\forall t\in T \tag{7}$$

$$E^{use}_{l,p,t}\geqslant\frac{e^{use}_{l,p}}{\tau_p+1}\sum_{t'=t-\tau}^{t}M^{in}_{p,t'} \quad \forall l\in L,\forall p\in P,\forall t\in T \tag{8}$$

Energy supplies and demands that are not specifically associated with any of the modelled processes are grouped as "other" and are assumed to be proportional to the hourly end-product demand. This includes the demands for the cooling tower, chemical preparation, raw water treatment and distribution, effluent treatment, boiler house, steam de-superheating/drainage and unspecified demands.

The mass and energy balances are closed by connecting the condensate return flows from all the processes and feedwater supply to the boilers with the storage level in the feedwater tank. See Eqs. 9 and 10, where W^s_t is the feedwater storage level each hour and W^{ext}_t is the hourly supply of make-up water. The feedwater is assumed to have a constant enthalpy and the storage level is limited by the size of the tank $w^{s,max}$, such that $W^s_t\leqslant w^{s,max}$, for each time-step. The level of heat recovered from the secondary heat system, Q^{sec}_t, is assumed to be constant.

$$W^s_{p,t}-W^s_{p,t-1}+\sum_{P}\left[S^{use}_{FW,p,t}-S^{gen}_{FW,p,t}\right]\leqslant \sum_{L_c}S^{dir}_{l_c,t}+S^{dir}_{LP,t}+W^{ext}_t \quad \forall t\in T \tag{9}$$

$$h_{FW}\left(W^s_{p,t}-W^s_{p,t-1}+\sum_{P}\left[S^{use}_{FW,p,t}-S^{gen}_{FW,p,t}\right]\right)\leqslant \sum_{L_c}h_{l_c}S^{dir}_{l_c,t}+h_{LP}S^{dir}_{LP,t}+h_W W^{ext}_t+Q^{sec}_t \quad \forall t\in T \tag{10}$$

The turbines are represented by the model developed by Aguilar et al. [28] according to Eqs. 11 and 12, where $S^{in}_{l,t,\theta}$ and $S^{ext}_{l,t,\theta}$ are the steam inflow and exhaust to/from turbine θ at each pressure level l and time t, and L_θ is the set of pressure levels to which turbine θ is connected. With this approach, the multi-stage turbine is modelled as a series of single-stage turbines. For each single-stage turbine, there is a linear relationship between the steam flow and power production, although the turbine efficiency decreases non-linearly with reductions in load. The turbines are further limited by their minimum and maximum inlet flows and maximum exhaust levels for each turbine stage, according to: $S^{in,min}_{l,\theta} \leqslant S^{in}_{l,t,\theta} \leqslant S^{in,max}_{l,\theta}$ and $S^{ext}_{l,t,\theta} \leqslant S^{ext,max}_{l,\theta}$.

$$S^{in}_{l,t,\theta} + S^{ext}_{l,t,\theta} \leqslant S^{in}_{l-1,t,\theta} \qquad \forall l \in L_\theta, \forall t \in T, \forall \theta \in \Theta \tag{11}$$

$$E^{gen}_{\theta,t} \leqslant \eta^{gen} \left(\sum_l \alpha_{l,\theta} S^{in}_{l,t,\theta} + \beta_\theta \right) \quad \forall t \in T, \forall \theta \in \Theta \tag{12}$$

Finally, all the variables, with the exception of the total cost, are restricted to non-negative values.

The model was implemented in GAMS [29] and solved using IBM ILOG CPLEX Optimizer [30] on a standard laptop computer, with solution times of a few minutes. The relatively short solution times despite the high time resolution (compared e.g. with the daily time resolution used by Svensson et al. [22]) were possible since neither investment decisions, integer variables for on/off operation of processes, nor non-linear relationships were included.

2.1.1. Model adaptions for campaign operation mode

In those scenarios where in which softwood and hardwood campaign operation is allowed, the model is extended to a mixed-integer programming model. All the mass flows E, M and S associated with the primary process chain (wood yard to pulp dryer) or the bark boiler are expanded with an additional dimension I spanning the two wood types. In these scenarios, the objective function contains the aggregated costs for the two wood types, according to Eq. 13.

$$min\ C = \sum_T \left[c^{el}_t \left(\sum_I \sum_P E^{use}_{i,p,t} - \sum_\Theta E^{gen}_{\theta,t} \right) + \sum_I \sum_P c^{ext}_{i,p} M^{ext}_{i,p,t} + c^w W^{ext}_t \right] \tag{13}$$

To keep the mill operating in campaigns, two binary variables A and B are introduced. The wood type variable $A_{i,p,t}$ defines which wood type i is allowed in each process p at each time-step t, and cannot have a value of 1 simultaneously for softwood and hardwood ($A_{softwood,p,t} + A_{hardwood,p,t} = 1$). The minimum and maximum load levels of the processes are constrained according to Eq. 14.

$$A_{i,p,t} m^{min}_p \leqslant M^{in}_{i,p,t} \leqslant A_{i,p,t} m^{cap}_p \quad \forall i \in I, \forall p \in P, \forall t \in T \tag{14}$$

$B_{p,t}$ is a switch variable, which has a value of 1 at any time-step t when there is a switch between hardwood and softwood operation in a process p. The relationship between the switch and wood type variables is then given by Eq. 15, and a maximum number of allowed switches can be set by: $B_{p,t} \leqslant B^{max}_{p,t}$.

$$B_{p,t} \geqslant A_{i,p,t-1} - A_{i,p,t} \qquad \forall i \in I, \forall p \in P, \forall t \in T \tag{15}$$

The storage mass balances are independently maintained for each wood type but are aggregated for the storage limit constraint, such that $\sum_i M^s_{i,p,t} \leqslant M^{s,max}$ for each process and time-step.

2.2. Assumptions and data

The model is run over a time set of 8,760 h (1 year). The boundaries are treated such that the last hour is connected to the first, thereby ensuring that all the storage levels are balanced over the total time set.

The linear coefficients between the material flow and flow of energy carriers for each process are calculated directly from the steady-state description of the Åforsk Model mills (softwood bleached market pulp) and are assumed to be identical, irrespective of the load.

Table 2 lists the assumed process capacity limits (steady-state and flexible), time durations, and associated storage sizes. If one excludes the intermediate storage times, the production line from wood to pulp takes 12 h, the recovery cycle takes 25 h and the lime cycle lasts 6 h. Storage inventories for the incoming wood and ready pulp are not included in the model; as a consequence, it is assumed that they do not limit the flexibility of the wood yard or the pulp dryer.

Table 3 presents the used steam header and condensate data, Table 4 gives the conversion factors between the material and energy flows in the processes and boilers, and Table 5 lists the turbine data. The turbine data are calculated based on the model developed by Aguilar et al. [28] and these data also correspond well with the steady-state model and with the data used by Svensson et al. (validated for measurements at a real-life site) [22].

Cost assumptions are listed in Table 6. All prices are assumed to be constant, with the exception of the cost for traded electricity where hourly spot prices are used for both the bought and sold electricity. Electricity prices for south-central Sweden (region SE3) for Year 2019 are used. These data were selected because they represent typical conditions for the Nordic region, with higher prices during wintertime than during summertime and a yearly averaged price of around 40 €/MWh. Perfect market integration is assumed, meaning that no taxes, subsidies or other administrative costs are considered. Results showing cost differences between scenarios should, therefore, not be interpreted as actual savings potential for a mill, but rather as the willingness to pay for different flexibility measures from the system perspective.

To understand the implications of the unusually high and volatile prices that occurred from October 2021 to September 2022, an additional model run was carried out with these prices. In this data-set, the prices range from −2 €/MWh to 800 €/MWh, with an average of 119 €/MWh.

2.3. Scenarios

Six scenarios were defined, where the model parameters related to capacity limitations and available storage were altered. Starting with a steady-state case, the freedom to vary the variables representing mass and energy flows increases with each scenario as more flexibility is added. A summary of the scenarios is presented in Table 7. The scenarios are labelled according to the combination of available flexibility in the steam supply (boilers) and steam/electricity demands, where BB represents the bark boiler, RB is the recovery boiler, and dem1, dem2 and dem3 indicate the different groups of flexible energy demands (steam and/or electricity-consuming processes) throughout the mill.

In the steady-state scenario, there is no over-capacity or storage available anywhere in the mill, which means that each process (including boilers) and turbine must operate steadily at the average level. This scenario acts both as a validation for the steady-state description in the literature and as a baseline for comparison with the

Table 2
Properties of the processes. The given capacities are steady-state values. The flexibility span for each process gives the capacity limits for the scenarios in which flexibility in the respective process is enabled. The digester and causticiser have dual inputs and outputs, as shown in Fig. 2.

Process	Capacity [t/h dry]	Duration [h]	Ext. supply lim. [t dry]	Storage size [kt dry]	Flex. span [%]
Wood yard	136	0	300	∞	0–120
Digester	170/34	3	51/10	30/1.5	
Washing stages	89	2		5	
Bleach plant	85	6		5	
Pulp dryer	83	1		10	80–120
Evaporation	146	23		20	80–120
Recovery Boiler	146	0		40	60–110
Causticiser	58/23	2	0/25	10/10	
Lime kiln	22	4		5	
Bark Boiler	9	0		50 (1.25)	60–140

Table 3
Properties of energy carriers included in the model.

Level	Pressure [bar]	Temperature [°C]	Enthalpy [MWh/100t]
HP	100	505	94.06
MP2	25	275	81.78
MP	9	200	78.53
LP	3.5	150	76.33
Cond4	10	190	22.42
Cond3	6	160	18.75
Cond2	3.5	140	16.36
Cond1	1	100	11.64
Cond0	1	35	5.75
Feedwater	4	146	17.31
Make-up water	1	15	1.75

other scenarios.

In scenario BB_lim, all processes in the production line and recovery cycle are still operated continuously at the steady-state level. Steam supply flexibility is allowed, utilising over-capacity in the bark boiler and condensing turbine coupled with the storage opportunities for bark and feedwater. The bark storage in this case is small, allowing for diurnal cycling of the bark boiler but limiting cycling over longer time periods. This scenario exemplifies how operations are planned in Swedish type mills so as to respond to the electricity price (from discussions with mill personnel).

In scenario BB/dem1, steam demand flexibility is introduced, in that steam demand for regenerative feedwater heating is allowed to vary and there is over-capacity available in both turbines. In addition, full-sized bark storage is available, enabling steam supply flexibility on the seasonal time-scale. However, due to the steady demand for bark from the lime kiln and the minimum load of the bark boiler (and the assumption that the storage is managed on the basis of a first-in, first-out principle), no single unit of bark is stored longer than 2 weeks.

In scenario BB/dem2, additional flexibility with regards to both electricity- and steam-consuming processes is added. Storage possibilities for bark, wood chips and wet pulp are enabled, and the wood yard and pulp dryer are allowed to vary between their respective lower and upper limits. See Table 2 for assumptions. Theoretically, for flexible processes, the ratio of high-load to low-load hours is restricted by the upper and lower load limits compared to the average operational level (e.g., 4 h up-time to compensate for 1 h down-time if the load span ranges from 0% to 125%). The maximum up-time is restricted by the storage capacity before the process, and the maximum down-time is restricted by the storage capacity after the process.

In scenario BB/dem3, steam and electricity demand flexibilities are also available in the evaporation plant. This process, which in reality is several process steps connected in cascade with intermediate storage, is in the model simplified as a process with 23-hour duration and with one associated storage tank for weak black liquor.

In scenario BB/RB/dem3, the steam supply flexibility is further enhanced, as the recovery boiler also presents over-capacity and storage opportunities. The recovery boiler operation is limited by a maximum up-/down-ramping speed.

2.3.1. Scenarios for softwood and hardwood campaign operation

Table 8 presents three scenarios for softwood and hardwood campaign operation, where the mill alternates between periods of softwood pulp production and hardwood pulp production to meet the demands for these two products. In the first scenario, Cmp_Steady, the campaigns follow a pre-defined pattern of 3 weeks of softwood operation followed by 1 week of hardwood operation repeatedly for 13 such 4-week cycles (total of 364 days). The capacities of the wood yard and bark boiler are up-scaled to ensure a steady supply of hardwood, as no additional supply of wood chips from a saw mill is assumed in this case. Due to a higher yield of cellulose from hardwood, the recovery cycle and lime cycle run on lower loads when processing black liquor from this stream. Storage of white liquor is allowed, to enable alternation between the two operational modes; in all other aspects, the mill operates continuously at the steady-state level throughout the campaigns.

In scenario Cmp_Flex_op, the campaigns themselves are still fixed, whereas the mill is assumed to have the full capacities available during both operational modes. As a consequence, there are over-capacities in the bark boiler and wood yard during the softwood campaigns and over-capacities in the recovery cycle and lime cycle during the hardwood campaigns. The storage unit sizes for intermediate products and feedwater, as well as the operational limits for the pulp dryer, are the same as in scenario BB/dem3. When combined, this allows for operational

Table 5
Properties of the modelled turbines. The given inlet and exhaust flows are steady-state values. The flexibility span for each turbine gives the inlet flow limits for the scenarios in which flexibility in the respective turbine is enabled. Corresponding flexibility spans are applied to the exhaust flows in these scenarios (upper limit only).

Turbine	Level	Inlet [t/h]	Exhaust [t/h]	coeff. $\alpha_{\theta,l}$ [MW/t]	offset β_θ [MW]	Flex. span [%]
BPT	HP	431		0.101	−13.5	50–120
	MP2		63	0.061		
	MP		111	0.071		
	LP		257			
CT	HP	210		0.352	−6.6	20–120
	Cond0		210			

Table 6
Cost data.

Resource	Cost [€/t]
Pulpwood	30
White liquor chemicals	370
Lime	120
Make-up water	0.2

Table 4
Energy consumption (positive values) and generation (negative values) per processed material for each process. Unit-less entities are tonnes of steam/water per tonne material.

	HP	MP2	MP	LP	Cond4	Cond3	Cond2	Cond1	Feed.	El. [kWh/t]
Wood yard										28
Digester			0.28							22
Washing st.			0.03							113
Bleach plant			0.08							79
Pulp dryer				0.88				−0.79		170
Evaporation			0.11	0.8			−0.86			16
Rec. boiler	−4.05	0.45	0.25		−0.37	−0.13			4.07	
Causticiser										86
Lime kiln										
Bark boiler	−5.45	0.06	0.19	0.28		−0.46			5.47	
Other		−0.04	0.03	0.13				−0.06	0.03	179

Table 7
Main scenarios overview.

Scenario	Flexible boilers	Flexible steam/electricity demands
Steady-state	N/A	N/A
BB_lim	Bark (limited)	N/A
BB/dem1	Bark	Feedwater heating
BB/dem2	Bark	Feedwater heating, Wood yard, Pulp dryer
BB/dem3	Bark	Feedwater heating, Wood yard, Pulp dryer, Evaporation
BB/RB/dem3	Bark, Recovery	Feedwater heating, Wood yard, Pulp dryer, Evaporation

flexibility in both the boilers and energy-demanding processes within each campaign.

In scenario Cmp_Flex_op/al, product flexibility on the energy demand side is introduced for the first time in this study. In this scenario, the demands for softwood pulp and hardwood pulp are the same as in the previous scenarios, although the time allocations of the campaigns (within each 4-week cycle) form part of the optimisation. A limit is imposed on the switch variable *B*, such that it can still only switch the wood type once every 4-week period. Flexibility within each campaign is allowed as in scenario Cmp_Flex_op.

To restrict the computational time, scenarios with campaign operations were solved for each 4-week period independently. Thereafter, the results were assembled into a complete sequence of 8,736 h.

3. Results

For the steady-state scenario ("Steady-state"), the results replicate the static description from Åforsk Model Mills in terms of all the material, steam, water, heat and electricity flows covered by the model. When different kinds of flexibility are introduced, the technical and economic indicators differ considerably between the scenarios. Initially in this section, the results for the interplay between the mill and electricity market for the six main scenarios are presented. In the subsequent sub-sections, the contributions of different flexibility measures and the internal dynamics in terms of the electricity, heat and material flows within these scenarios are analysed, followed by an economic comparison of the scenarios. Finally, the results for the three campaign operation scenarios are presented, illustrating flexibility in a pulp mill that is producing softwood pulp and hardwood pulp in different campaigns.

3.1. Interplay with the electricity market

Fig. 4 shows the duration curve of the pulp mill's total net electricity production, sorted in decreasing order for each scenario. Table 9 lists the values for electricity generation and consumption, shifted electricity, maximum and minimum net generation, and hours as net producer and net consumer for the six main scenarios. The aggregated consumption of electricity is the same in all scenarios, while the total electricity production is similar in the scenarios Steady-state and BB_lim and 0.5% higher in the three more-flexible scenarios, leading to a slight increase in the amount of sold electricity in these scenarios. The major difference between the scenarios in terms of energy is that a greater amount of net production is shifted in time as more flexibility becomes available. Shifted energy corresponds to the aggregated decrease in net production, seen to the right of the intersection with the steady-state level in Fig. 4 (which is equivalent to the aggregated increase seen to the left of the intersection, minus any difference in production). Furthermore, the

Table 8
Campaign operation scenarios overview.

Label	Flex. operation	Flex. allocation
Cmp_Steady	N/A	N/A
Cmp_Flex_op	Yes	N/A
Cmp_Flex_op/al	Yes	Yes

span between the maximum and minimum electricity net generation levels increases throughout the scenarios, as the maximum capacity is increased and the minimum capacity is decreased. The mill remains a net producer of electricity for all the hours in all the scenarios, except for BB/RB/dem3 in which flexibility is available in the recovery boiler; in this scenario the mill is a net electricity consumer for 9% of the hours.

3.2. Implications of the different flexibility measures

Fig. 5 shows the differences in net electricity production for each flexible scenario compared with the steady-state scenario, for the top and bottom decile hours of the net electricity production (shaded sections in Fig. 4). In scenario BB_lim, in which only steam supply flexibility is available, the net increase in the top decile is enabled by operating the bark boiler at its rated capacity and increasing the production level in the condensing turbine accordingly. In the bottom decile, the bark boiler is operated at its minimum level and the condensing turbine output is lowered accordingly. In scenario BB/dem1, in which steam demand flexibility is introduced, the bark boiler is also operated at maximum load and a further increase in electricity production is enabled by shifting production from the back-pressure turbine to the condensing turbine, increasing it up to the capacity limit of the condensing turbine. In scenarios BB/dem2 and BB/dem3, the net production is further increased as the electricity consumption levels are reduced in the wood yard, pulp dryer and evaporation plant. The net production level in the bottom decile is reduced further in these scenarios, allowing for a higher average net production over the remainder of the time-set. In scenario BB/RB/dem3, the flexibility in steam supply from the two boilers is sufficiently high for both turbines to be operated at high load during the top decile hours and at low load in the bottom decile, leading to the large span of the net electricity production profile.

Fig. 6 shows the differences in net steam production between each flexible scenario and the steady-state scenario. The aggregate net steam production (production minus consumption, black diamonds in Fig. 6) is

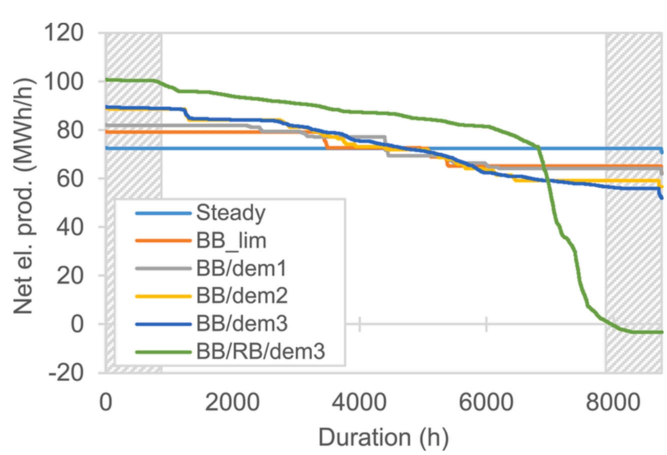


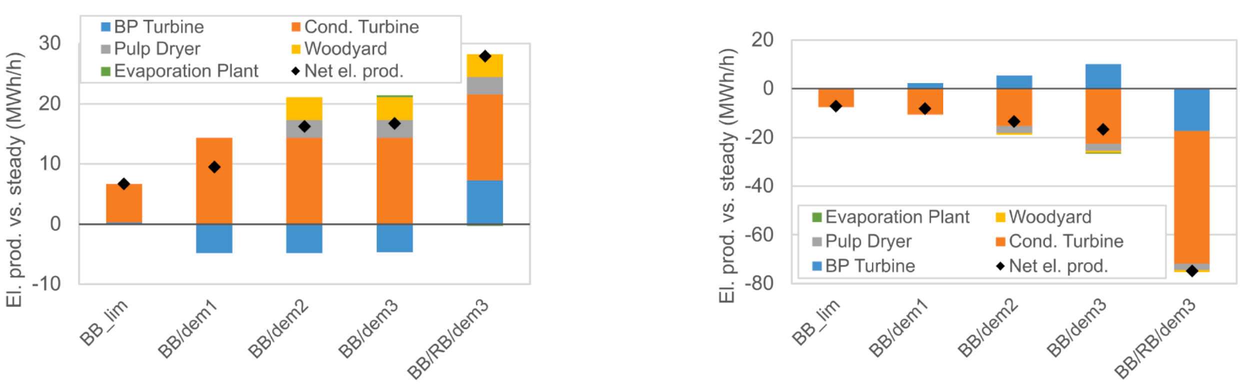
Fig. 4. Duration curve of the hourly net electricity production (production minus consumption). The top and bottom deciles referred to in the text are highlighted.

Table 9
Key technical indicators for the six main scenarios.

Result	Unit	Steady	BB_lim	BB/dem1	BB/dem2	BB/dem3	BB/RB/dem3
Produced electricity	GWh	1 166	−2	+4	+4	+4	+4
Consumed electricity	GWh	531	±0	±0	±0	±0	±0
Shifted energy	GWh	0	+25	+29	+41	+44	+111
Max. net generation	MW	72.5	+7	+10	+17	+17	+29
Min. net generation	MW	72.5	−10	−11	−16	−21	−76
Hours as net consumer	%	0	±0	±0	±0	±0	+9

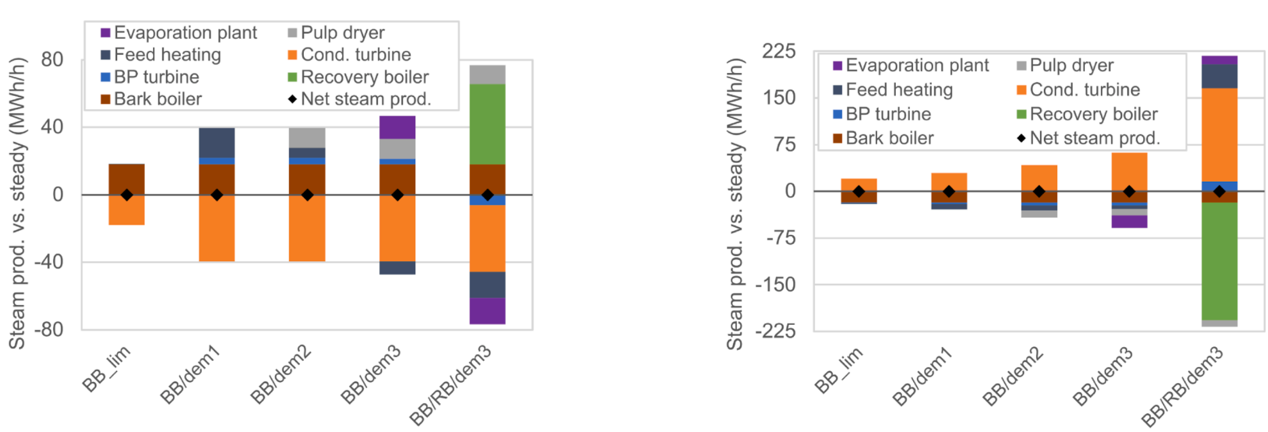
always zero as no steam is exchanged with the system surroundings. Steam is shifted from being used for heating demands in the steady-state scenario to being increasingly used for electricity production in scenarios BB_lim to BB/dem3. This shift is enabled by reduced loads in the pulp dryer, evaporation plant and feedwater heating, all of which consume medium- or low-pressure steam from the exhausts of the back-pressure turbine. The available options for heat demand reduction in the pulp dryer in scenarios BB/dem2 and BB/dem3 and the evaporation plant in scenario BB/dem3, do not allow for an increased production capacity compared to BB/dem1, as the condensing turbine is already operating at maximum; however, they result in larger amounts of energy being shifted. Feedwater heating is used to a lesser extent for flexibility when other options for flexible steam demand are available. In scenarios BB/dem2 and BB/dem3, there is a synergy between the steam demand flexibility and the electricity demand flexibility, because, when the loads of the pulp dryer and evaporation plants are reduced during high-production hours, they both support increased electricity production because their steam demands are reduced and, at the same time, directly reduces the levels of electricity consumption in the processes. The opposite effect is seen for low-production hours. In the BB/dem3 scenario, for the top-decile hours of net electricity production, the feedwater heating is operated in the opposite direction, thereby balancing the reduced heat demand from the evaporation plant. In the most-flexible scenario BB/RB/dem3, the pulp dryer is steered by its electricity demand, while the feedwater heating and evaporation plant (which is only a minor electricity consumer) follow the operation of the back-pressure turbine.

Load duration curves over the entire time-set for steam production in



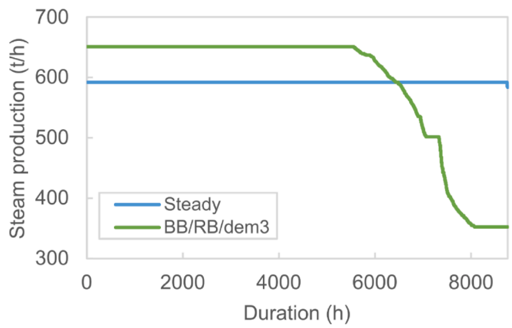
(a) High-production decile (b) Low-production decile

Fig. 5. Difference in level of net electricity production between the flexible scenarios and the steady-state scenario, for the top and bottom decile hours of the total net electricity production. Coloured bars show the contributions from each flexible turbine and electricity-consuming process.

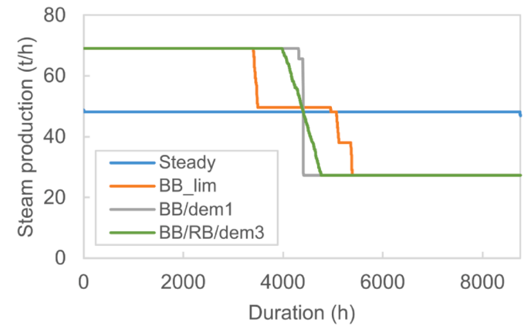


(a) High-production decile (b) Low-production decile

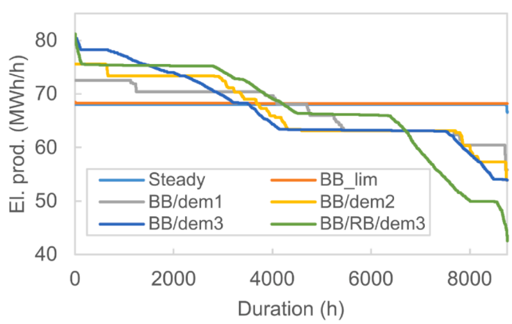
Fig. 6. Difference in level of net steam production between the flexible scenarios and the steady-state scenario, for the top and bottom decile hours of the total net electricity production. Coloured bars show the contributions from each flexible boiler and steam-consuming process. Note the different scaling in panels a and b.



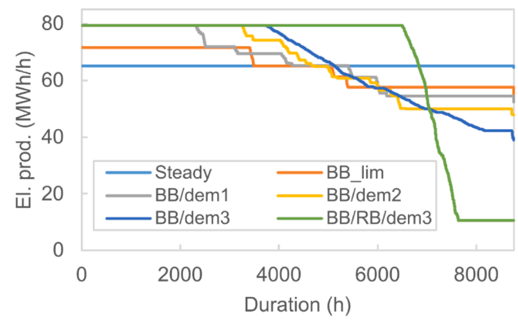
(a) Recovery boiler steam production.



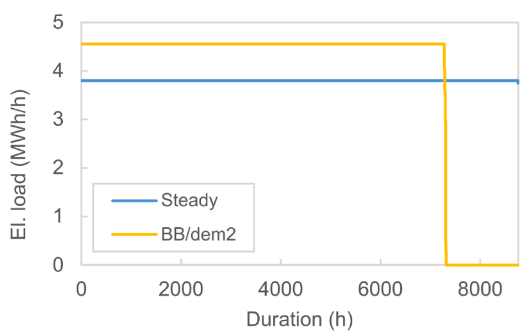
(b) Bark boiler steam production.



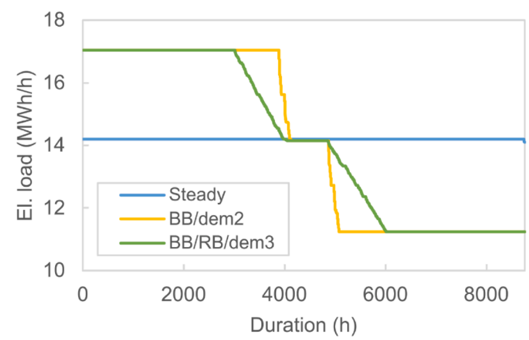
(c) BP turbine electricity production.



(d) Cond. turbine electricity production.



(e) Wood yard electricity consumption.



(f) Pulp dryer electricity consumption.

Fig. 7. Duration curves of steam production from the two boilers (a-b), electricity production from the two turbines (c-d) and electricity consumption for the wood yard and pulp dryer (e-f). The MP and LP steam loads for the pulp dryer are proportional to the electricity load. The loads are sorted in descending order, for each graph separately.

the boilers, electricity generation in the turbines, and electricity consumption in selected processes are presented in Fig. 7. Sub-Figs. 7a and 7b show the duration curves of the high-pressure steam generation in the recovery boiler and bark boiler, respectively. The recovery boiler is only flexible in scenario BB/RB/dem3, where the ratio of high-load to low-load hours reflects the asymmetric operation span of 60–110% of the steady-state level. The gradual transition from the minimum to maximum level reflects the limited ramping rate and the need to match the steam demands of slower processes. The bark boiler has a symmetric operation span centred on the steady-state level (60–140%), where the number of high-load hours equals the number of low-load hours. In scenariosBB/dem1-3, where the full bark storage size is available, the bark boiler is operating only at the minimum and maximum limits, indicating weak dependence upon constraints other than capacity limits. In scenario BB_lim, the limited storage causes the bark boiler to operate in between these limits for some of the hours. In scenario BB/RB/dem3, in which also the recovery boiler is flexible, the duration profile of the bark boiler is slightly different, due to the fact that during some hours, the overall steam flexibility is limited by the process and turbine capacity limits rather than by the steam supply.

Sub-Figs. 7c and 7d show duration curves of electricity production from the two turbines. In the most-flexible scenario, BB/RB/dem3, the condensing turbine is able to operate close to its capacity limits, as its operation is independent of other steam demands in the mill (although it is still limited by the ramping rate of the recovery boiler). For all other scenarios, the load duration curves of both turbines reflect operational patterns that are limited by other processes in the mill, and thus the turbines cannot operate fully to maximise the value of the potential electricity generation. For scenarios BB/dem1-3 and BB/RB/dem3, there is sufficient flexibility of the steam supply and demand for the condensing turbine to operate at its maximum capacity for a considerable duration, which increases with each added flexibility measure. A tighter constraint on the capacity of the condensing turbine would limit the capacity span of the net electricity production, although it would not necessarily affect the results in terms of the amount of shifted energy. The back-pressure turbine only uses its full capacity for a few hours in the two most-flexible scenarios BB/dem3 and BB/RB/dem3, indicating that marginally narrowing the operation span for this unit has a weaker impact on the results.

Sub-Figs. 7e and 7f show the duration curves for the electric loads of the wood yard and pulp dryer. In a comparison of the wood yard and pulp dryer, certain aspects are noteworthy. The wood yard, which can be controlled independently from the steam system, operates in scenario BB/dem2 at its full capacity for 7,225 h; otherwise, it is not in operation. The patterns are the same in all scenarios where flexibility is enabled for the wood yard (not shown in the figure). The position of the intersection with the steady-state line at 7,225 h originates from the asymmetric operation span between 0% and 120% relative to the average operation. The effect on the total net production of stopping the wood yard is evidenced as a distinct step for scenarios BB/dem2 and BB/dem3 at around Hour 1,400 in Fig. 4. In contrast, the pulp dryer shows symmetrical load duration, as its assumed operational span is centred on the steady-state level. Similar to the wood yard, it is mainly operated in direct response to the electricity price. In the most-flexible scenario BB/RB/dem3, the pulp dryer operation differs slightly from its profile in the less-flexible scenario BB/dem2, as there is a conflict between the optimal operations for electricity production and consumption. The plateau observed between Hour 4,000 and Hour 5,000 in Sub-Fig. 7f, corresponding to the steady-state level, originates from the 2-h throughput time of the process, forcing an intermediate level when shifting between low and high loads.

3.3. Operational patterns and limitations to flexibility

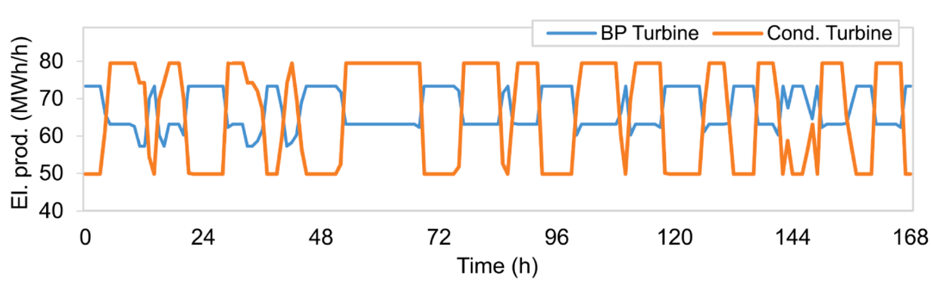
In this section, the load duration curves presented above for the complete time-set are complemented with results showing the time-resolved dynamics of process operation. The different dispatch strategies between scenarios BB_lim and BB/dem1-3, with varying degrees of flexibility in the bark boiler and energy-demanding processes, compared to BB/RB/dem3, in which there is flexibility also in the recovery boiler, are illustrated in Fig. 8, showing the load curves for 1 week (April 1–7) of operation of the back-pressure and condensing turbines. The daily pattern follows the effects seen for the top and bottom deciles in the net electricity generation (Fig. 5), as the two turbines are operated in a mirrored pattern for scenario BB/dem2 (which is also the case for scenarios BB_lim, BB/dem1 and BB/dem3) but synchronised for scenario BB/RB/dem3.

Fig. 9 shows histograms over the down-ramping events for the wood yard, pulp dryer, bark boiler and recovery boiler. Starting with the wood yard, for which down-ramping events are equal to full stops, it is clear that the operation is similar in all the scenarios in which flexibility is available. The theoretical maximum down-time is never reached. Instead, the dispatch is tightly linked to the price variations, which under the assumed electricity prices (SE3 2019) are primarily caused by variations in the demand. As shown in the figure, the wood yard operation is typically stopped for 1–7 h to avoid morning and afternoon peaks. Durations of between 14 and 17 h are also common, corresponding to full-day stops covering both the morning and afternoon peaks.

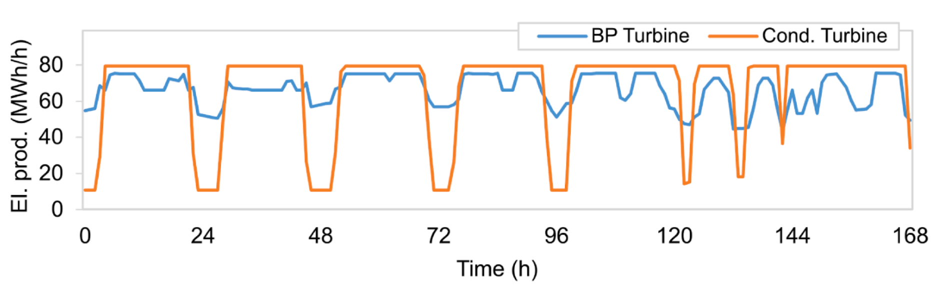
The operation of the pulp dryer (Sub-Fig. 9b) is also carried out in direct response to electricity prices, with reduced loads during the morning and afternoon peaks, with slightly longer down-ramping events than were seen for the wood yard due to the longer duration of the process. Sub-Figs. 9a and 9b together show that the electricity demand is frequently shaved by up to 11 MW (according to input data) for periods of 2–5 h.

The bark boiler (Sub-Fig. 9c) is typically operating at low load during night-time when electricity prices are low, corresponding to the down-ramping occasions between 6 and 9 h in duration, reducing the overall steam production to save bark for increased operation during daytime. In scenario BB_lim, with limited bark storage, there are more low-load segments of duration 1–24 h compared to the more-flexible scenarios, while in scenarios BB/dem2-3 and BB/RB/dem3, in which a larger bark storage is allowed, there are more low-load segments of duration ⩾25 hours, with the longest spanning over several weeks during summer-time.

When flexibility is available in the recovery boiler in scenario BB/RB/dem3 (Sub-Fig. 9d), it is operated in a manner similar to the bark boiler in scenario BB_lim, i.e., with low-load periods during the night-time for typically 5–8 h. When the recovery boiler provides flexibility for these periods in scenario BB/RB/dem3, the bark boiler has fewer down-ramping occasions compared to the other scenarios. Furthermore,



(a) Scenario BB/dem2.



(b) Scenario BB/RB/dem3

Fig. 8. Turbine operation over an example period of 7 days (April 1–7).

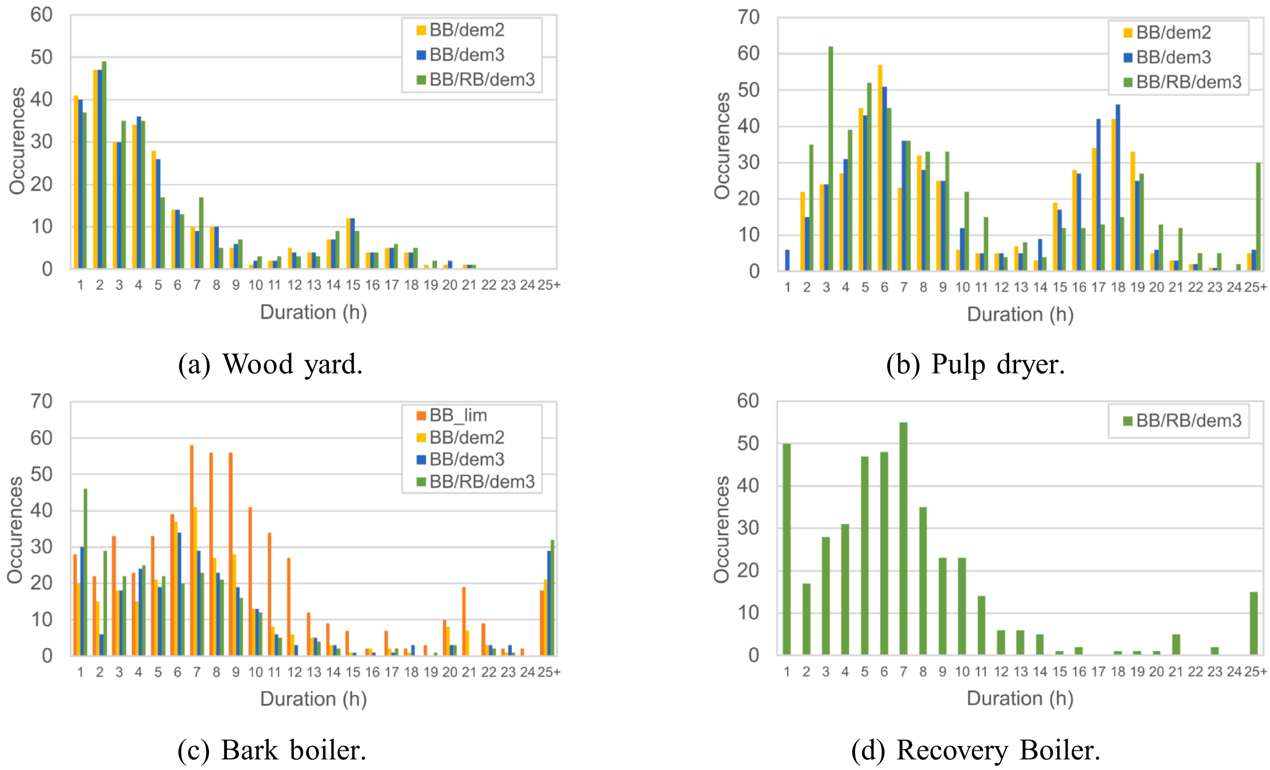


Fig. 9. Frequency plots of flexible processes, showing a histogram over segments of deviations from the maximum load. Note that all segments with durations ⩾25 hours are grouped in the last bar.

in this most-flexible scenario, both boilers respond frequently to price variations of 1-hour duration.

Fig. 10 shows how the storage units for bark, strong black liquor and feedwater are used over an illustrative period of 7 days. Sub-Fig. 10a shows that the bark storage is large in relation to the diurnal and intra-diurnal variations in the bark feed from the wood yard and in the bark consumption in the bark boiler, and thus the bark storage size has no direct impact on the operation of these processes over the displayed time scale.

Sub-Fig. 10b shows that with the assumed flexibility span and tank size, the strong black liquor storage is, in general, sufficiently large for the evaporation plant and recovery boiler to be operated independently, so as to manage diurnal variations. However, it should be noted that these results are derived from a model that has perfect foresight, so it does not consider any unexpected events. In reality, there can be a need to reserve storage as buffer, and unlocking the flexibility may necessitate additional storage volumes.

Sub-Fig. 10c shows how the feedwater storage is used to balance variations in the incoming heat flows and supply to the boilers. In scenarios BB_lim to BB/dem3, when the recovery boiler is operating steadily, the storage is large in relation to the variations in feedwater usage for the bark boiler, and the variations in storage level are mainly driven by the flexibility of the low-pressure steam for feedwater heating. The storage is filled up during low-net-production hours when the BP turbine is prioritised, and is emptied during high-net-production hours when the condensing turbine is prioritised. In scenario BB/RB/dem3, the storage level is also strongly affected by variations in the feedwater demand of the recovery boiler. In both scenarios, the storage limit is a binding constraint for most of the time-steps, suggesting that a larger storage unit (or an additional heat source) could unlock additional flexibility. Furthermore, the speed with which make-up water can be supplied is a limiting parameter for the cycling of the feedwater storage.

In summary, none of the flexible processes are limited by their storage sizes for the matching of diurnal and intra-diurnal electricity price variations. Storage tank sizes for wet pulp and black liquor are, however, found to be limiting for flexible operation on time-scales that range from a few days to weeks.

Fig. 11 shows how bark and wood chip storage stacks are used to handle seasonal variations. Sub-Fig. 11a shows that bark is stored to enable a higher level of operation of the bark boiler during months with higher electricity prices. The figure also shows the aggregated level of bark generation from the wood yard in each month. The bark storage size is used to its full capacity and limiting the flexibility over the full time period. The variations in the mass flow to the wood yard across the months show the impact of the limited bark storage on the operation of the wood yard. Rather than directly following the electricity price, the operation of the wood yard is balanced to reduce the costs of its own electricity consumption while also feeding the bark boiler with bark during high-price months.

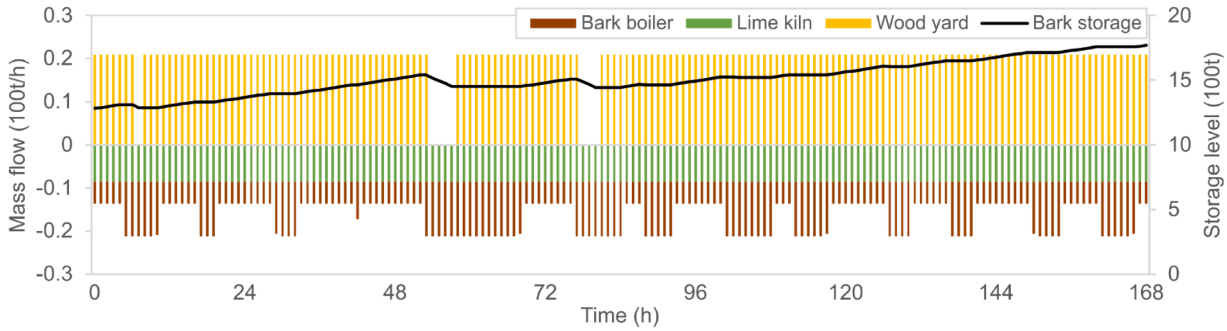
When the model was run with the possibility to turn off the bark boiler completely (introducing a binary variable in the lower capacity limit) it exploited this opportunity for a few weeks during the summer. The impact on the overall results was limited, although it enabled the wood yard to be operated in a more independent fashion, as there was more bark available for the rest of the year.

Sub-Fig. 11b shows that the wood chips storage is large in relation to the variations in wood chips feed from the wood yard, and never used to its full capacity. This implies that the seasonal flexibility of the wood yard operation is not limited by the need to supply the digester with wood chips. This need would, however, become limiting if the wood yard operation was less dependent on the bark boiler.

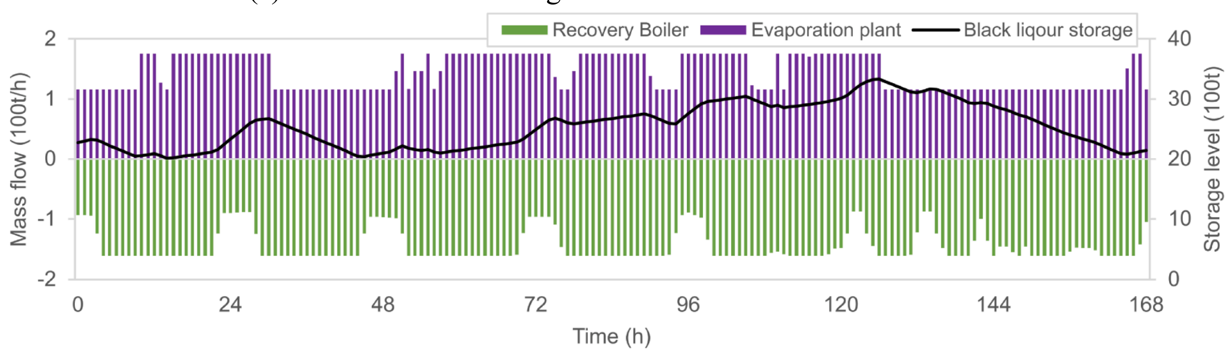
3.4. Economic value of flexibility

The aggregated value of the net electricity production (production minus consumption) at each time step increases gradually as more flexibility is introduced with each scenario.

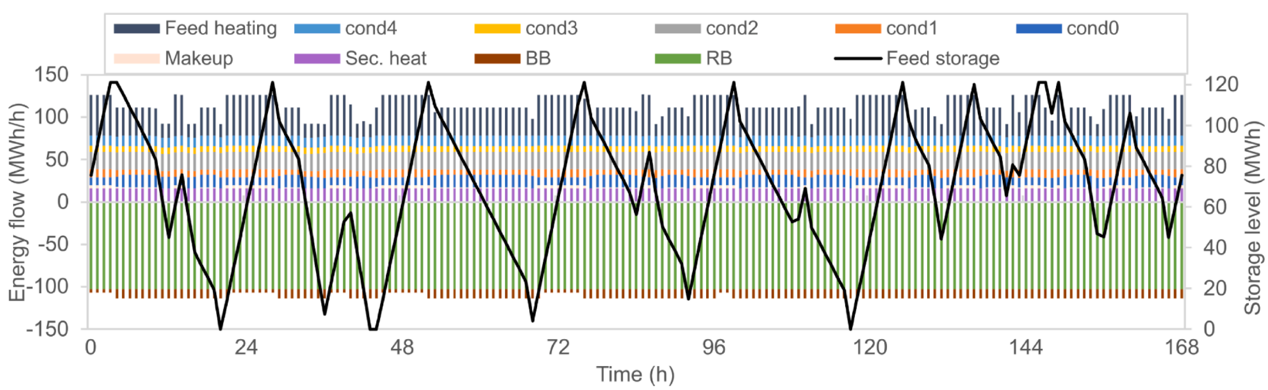
Fig. 12 shows the aggregated value of net electricity production



(a) Bark flows and storage level. Scenario BB/dem2.



(b) Strong black liquor flows and storage level. Scenario BB/ RB/dem3.



(c) Feedwater flows and storage level (energy units). Scenar io BB/dem2.

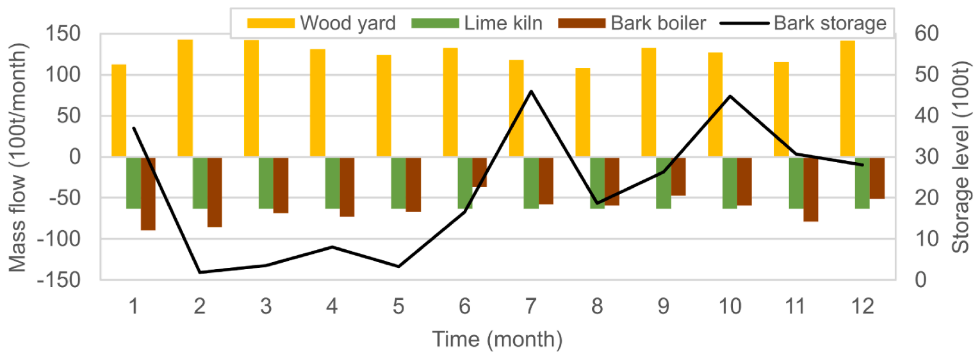
Fig. 10. Storage utilization over an example period of 7 days.

compared to the steady-state scenario, and more economic indicators are presented in Table 10. The gains in net value range from 0.7% in scenario BB_lim to 8.1% in BB/RB/dem3, corresponding to 0.2–2.0 M€ annually for the type mill. There are potential gains from both increased income for sold electricity (blue bars in Fig. 12) and reduced costs for consumed electricity (orange bars in Fig. 12), although the gain is clearly larger on the income side. When scenario BB_lim was run with the same size of bark storage as the more-flexible scenarios (BB/dem1-3), the net value increase was 1.3%. Assuming that the contribution from steam supply flexibility is the same in scenarios BB/dem1-3, the income increase can be divided into two roughly equal parts, with steam demand flexibility contributing 1.2–1.6% in added value. The remaining part of the accrued gain in net value, from electricity demand flexibility, corresponds to reduced costs, contributing 0.6–0.8% in added value.

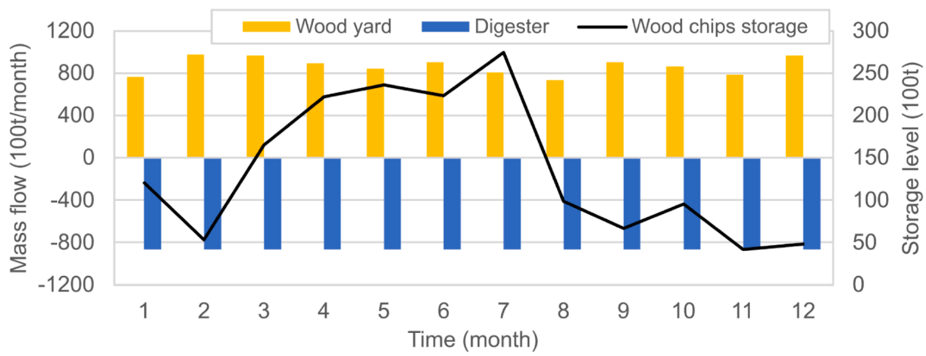
In scenario BB/RB/dem3, where flexibility is available in the recovery boiler, steam supply flexibility dominates the operational pattern and makes the largest contribution to the increase in net value. The direct savings from electricity demand flexibility (indicated by the orange bar) are slightly smaller in scenario BB/RB/dem3 than in BB/dem3, showing the effect on the economic value of the pulp dryer being operated to support power production in the back-pressure turbine in scenario BB/RB/dem3, rather than reducing the cost of its own electricity consumption.

For model runs with the unusually high and volatile electricity prices that existed between October 2021 and September 2022, the difference between the scenarios is much greater than for the Year 2019 case, in both absolute and relative terms. The increase in net electricity value for scenarios BB_lim to BB/dem3, compared to the steady-state scenario, ranges from 5% to 25%, corresponding to an increase in net value of 4–20 M€. The absolute value increase for the 2021–2022 case is 10-times the value in Year 2019 for the most-flexible scenario BB/RB/dem3, despite the fact that the average electricity prices were only 3-times higher.

The model does not consider interactions with any market other than the electricity market, whereas in reality by-products such as bark can be traded externally. Fig. 13 shows the internal value of bark over the



(a) Bark flows and storage level. Scenario BB/dem2.



(b) Wood chips flows and storage level. Scenario BB/dem2.

Fig. 11. Monthly aggregated storage utilization.

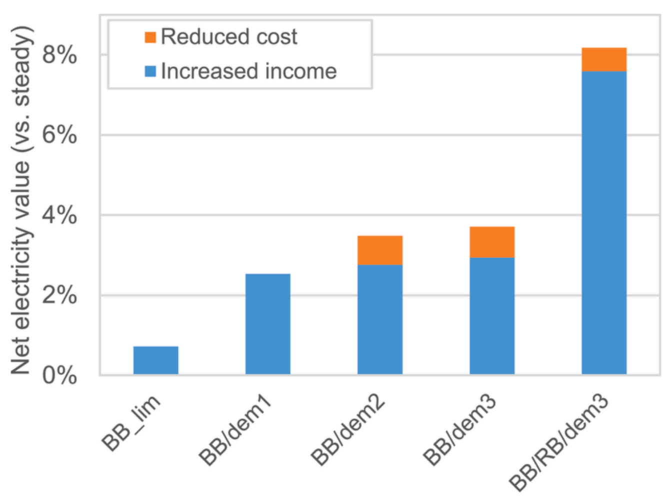


Fig. 12. Comparison of the scenarios regarding the market value of net electricity production. The steady-state scenario is used as baseline.

year for four of the scenarios (obtained as the marginal value of Eq. 4 converted to value per energy unit). For the steady-state scenario, the value of the bark is proportional to the electricity price, and the more storage possibilities that are added the more the variations in the bark values are evened out. The steady values for scenarios BB/dem2 and BB/RB/dem3 are close to the average Swedish market value in 2012–2021 for solid biomass by-products of 16 €/MWh [31]. Whether there is a value or not associated with trading bark in the external market thus depends on the internal storage possibilities and on the price variations in the market.

3.5. Flexibility from softwood and hardwood campaign operation

The key technical and economic indicators for the different scenarios with campaign operation are presented in Table 11. In terms of economics, the flexibile mill operation in scenario Cmp_flex_op increase the net electricity value compared to the baseline scenario Cmp_steady with 7.6%, i.e., similar to the difference between the least-flexible and most-flexible scenarios in the single wood type model.

Most of the increase in value is obtained during the hardwood campaigns, when the recovery boiler is available for operational flexibility. When the allocation of hardwood campaigns within each 4-week campaign cycle is optimised in scenario Cmp_flex_op/al, these are moved to periods with high electricity prices, and the difference in the

Table 10
Key economic indicators for the six main scenarios.

Result	Unit	Steady	BB_lim	BB/dem1	BB/dem2	BB/dem3	BB/RB/dem3
Sold electricity	GWh	635	−2	+4	+4	+4	+7
Bought electricity	GWh	0	±0	±0	±0	±0	+2
Average selling price	€/MWh	40.55	+0.42	+0.74	+1.13	+1.22	+3.01
Average buying price	€/MWh	N/A	N/A	N/A	N/A	N/A	25.94
Net electricity value	M€	25.8	+0.7	+0.9	+1.0	+2.1	

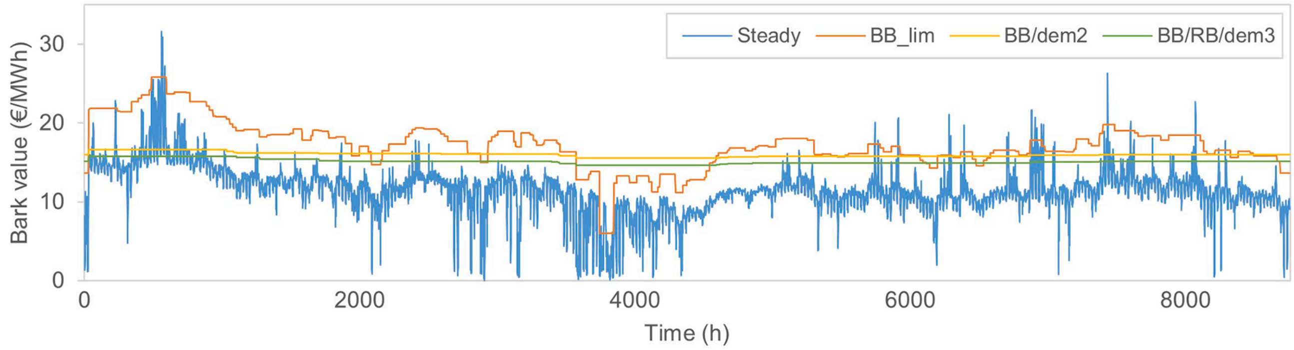


Fig. 13. Marginal value of bark over the modelled time-set for the different scenarios.

Table 11
Key technical and economic indicators for the three campaign operation scenarios.

Result	Unit	Cmp_steady	Cmp_flex_op	Cmp_flex_op/al
Generated electricity	GWh	1 115	+4	+4
Consumed electricity	GWh	517	±0	±0
Shifted energy	GWh	0	+74	+73
Max net generation	MW	81	+17	+17
Min net generation	MW	44	−45	−45
Hours as net consumer	%	0.0%	1.6%	2.1%
Sold electricity	GWh	599	+4	+4
Bought electricity	GWh	0	+0.05	+0.1
Average selling price	€/MWh	40.74	+2.06	+2.10
Average buying price	€/MWh	N/A	14.93	16.71
Net electricity value	M€	24.38	+1.41	+1.43

value of traded electricity between the softwood and hardwood campaigns is, thereby, increased. However, the total value of traded electricity over the total time period is the same as in scenario Cmp_flex_op.

4. Discussion

A comparison of the results from the model runs with the electricity prices from Year 2019 and the period of 2021–2022 shows that flexibility is more valuable in systems that experience volatile electricity prices. This means that if the share of variable renewable electricity generation is increased, leading to a future electricity market where electricity prices are highly weather-dependent, introduction of the proposed flexibility measures will be more-relevant than in the current context. With current electricity prices, the flexibility measures are primarily used to balance price variations on diurnal and seasonal timescales. For a wind power-dominated system, characterised by variations on a time-scale of days-to-weeks, it seems likely that the optimal frequencies of reduced-load events in boilers and processes would look different. In such systems, storage of, for example, wet pulp and liquors might also be more-limiting than was seen in the present study. Future research could continue to explore the role of the flexible pulp mill in different electricity system scenarios, covering feedback effects on the electricity price when demand response is made available in multiple sectors.

A limitation of the present work is that the potential for flexible operation will differ across real sites, and a detailed review of available storage units and the operational limits of processes, boilers and turbines, including available over-capacity, needs to be carried out to reach a site-specific conclusion. The results indicate, however, that the operational limits of boilers, turbines and production processes are often more-limiting than storage unit sizes. If there is no or too little over-capacity in the back-pressure turbine, steam will need to by-pass the turbine whenever a steam-consuming process is operated above the steady-state level. This represents a trade-off between supply-side and demand-side flexibilities, which was not seen in the present study due to the assumptions made.

If processes are allowed a broader operational span than that applied in this study, a more-advanced representation of how the energy consumption in each process depends on the material load may be needed. The assumption of proportionality made here entails a risk of over-estimating the impact of flexible operation on the energy flows, i.e., if the process has a constant base-load demand independent of the load. Furthermore, the model did not cover any seasonal variations in the steam demand for the production processes. In cold climate conditions, a higher steam demand during the winter season may decrease the available over-capacity in the bark boiler.

The secondary heat system in the mill was not covered by the present study. Therefore, there is a risk that some of the measures explored here would be limited by bottlenecks in this system when implemented in a real mill. However, this should not have a significant impact on the fundamental mass and energy balances, as any heat shortages in the secondary heat system could be covered by a minor fraction of low-pressure steam from the primary heat system, which would only marginally reduce the level of electricity production.

In the present study, it was assumed that no over-capacity was available in the washing and bleaching stages. These stages are relatively heavy consumers of electricity and typically have storage opportunities. Thus, in case there are mills in which there is over-capacity for these processes, it would be relevant to include them in a flexibility assessment. There may also be opportunities for demand-side flexibility in the waste-water treatment, which was excluded from the present study as the process water system was not modelled. Furthermore, integrated mills that produce paper could be the subject of another assessment, as they have a high level of electricity consumption in the paper-producing machines. Integrated mills that produce both market pulp and paper could have additional opportunities for product flexibility.

If the electricity prices are higher than the value of the produced pulp, it could be worthwhile to reduce also the total pulp production. When the model was not restricted to use bark for power production, it was also observed that for some hours a larger share of the wood was passed directly to the bark boiler. In situations with higher electricity prices or lower wood prices, this effect could be more-pronounced. The model could also be expanded to allow for trade in bark or for other external fuels to be used in the bark boiler.

Several large pulp mills in Sweden also supply district heating to nearby communities. This aspect was not included in the study because the heat used for this purpose is low-temperature waste heat from the secondary heat system. Therefore, it does not affect the dynamics of the studied system or the techno-economic analysis thereof.

The presented method is not intended as a practical measure for operational support, although it demonstrates the benefit of using similar tools for joint optimisation of the production line and energy management. The optimisation model operates with perfect foresight, which would not be achievable in reality. However, most of the planning is performed over a time horizon of a few days, which means that price forecasts should be accurate, and the seasonal differences are similar from year to year. Furthermore, although real-time optimisation based on price forecasts would be needed to unlock the full potential, much of the operational profiles in the results follow diurnal and seasonal patterns, and part of the potential flexibility could be implemented through rule-of-thumb scheduling.

The model gives an estimate of the potential value of flexibility, which should for practical implementation be weighed against the cost for flexibility. Such costs could stem from increased maintenance or potential life-time reductions for items of equipment linked to wear and tear from frequent cycling of the boilers, turbines and process units. The costs related to risks should also be considered, e.g., if there is an increased risk of production stops due to frequent load changes or because there is less storage available as buffer when the storage units are used for operational flexibility. Furthermore, there could be costs associated with organisational barriers, as discussed by Lawrence et al. [32].

The results show that one of the most-effective flexibility measures is steam demand flexibility, whereby the priority is alternated between the back-pressure turbine and the condensing turbine. In the current methodology, the back-pressure turbine is prioritised during part of the day, partly to support feedwater heating. If the temperature in the feedwater tank were allowed to drop below the steady-state level, compensating for the energy loss with additional fuel in the boilers, this would allow for increased flexibility in the turbines. In a real mill resembling the type mill, additional value could be created using steam storage, as proposed by Panuschka & Hoffmann [15], or through the addition of another heat source. The results also show that any over-capacity in the recovery boiler has a potent impact on the flexibility potential. For new investments in recovery boilers, this benefit should be weighed against the increased costs. For existing mills, this potential could be unlocked by investing in a lignin extraction plant or by increasing the use of hardwood in the production process.

Electricity demand flexibility has a relatively weak impact on the results, due to the limited share of demand that is assumed to be flexible. However, these measures have a noteworthy impact during the most-valuable hours, and they may be easier to implement than measures on the steam side, as they are less-integrated with other mill processes. A first step towards implementation could be to account for electricity prices in the scheduling of diurnal and annual maintenance stops. Usually, Nordic pulp mills halt production for maintenance stops during a few weeks of the summer, which was not accounted for in the presented scenarios. It could be proposed to leave the bark boiler out of operation for some additional time period in conjunction with these stops and to perform any annual maintenance of the wood yard during wintertime. As proposed by Jannasch et al. [24], regular knife exchanges in the wood chopper could also be scheduled during high-price hours.

In a wider perspective, the near-future development of chemical pulp mills will not only be driven by changes in the electricity sector. Policies restricting the use of fossil fuels and materials may increase the value of the biogenic carbon atoms, which will incentivise extracting lignin from the black liqour. Other policies, aiming for negative emissions, may incentivise the implementation of carbon capture at chemical pulp mills. Implementation of any of these technologies would considerably impact the energy balances in the mill, decreasing the net electricity production. These trade-offs have been mapped by Tomani et al. [33] and Onarheim et al. [34], but it remains for future research to investigate how these technologies are influenced by intra-diurnal variations in the electricity price, which would require an analysis similar to the one performed in this work.

5. Conclusion

A novel methodology has been established for joint optimisation of pulp production and energy management at a chemical pulp type mill, in response to electricity market dynamics on time scales that range from hours to seasons. The methodology provides insight into the dynamic interactions that occur between the different parts of the mill, and both the synergies and conflicts between different flexibility measures are identified, underlining the importance of joint optimisation.

The results show that the mill remains a net producer of electricity during most of the operational hours, even with flexible operation. The span of the lowest to highest momentary net production ranges from 17 MW in the least-flexible scenario to 105 MW in the most-flexible scenario; thereby, 25–111 GWh of electricity are shifted from low-value to high-value hours. The flexibility is mainly used to match the diurnal variations in electricity demand, although long-term storage of bark also enables a seasonal pattern of operation for the bark boiler.

For the type mill investigated, intermediate product storage units are sufficiently large to support diurnal variations, while the bark storage system is potentially limiting to seasonal variations. The capacities of the processes, turbines and boilers, as well as the availability of thermal storage, are found to be limiting factors for flexible operation.

With the proposed measures for flexible operation, the value of traded electricity can be increased by 1–8%, based on the electricity prices in Year 2019. This can be achieved without investments in additional capacity, through increased integration with the electricity market. For the modelled type mill, producing 2000 ADt/d of pulp, this corresponds to 0.2–2.0 M€ per year. However, for the more-recent electricity prices as of Year 2022, the value can be approximately 10-fold higher.

The increased value of traded electricity is attained through a combination of flexibility in the steam supply, steam demand, and electricity demand. In the most-flexible scenario, where over-capacity is available in the recovery boiler, steam supply flexibility has a dominating impact on the value of the traded electricity. In the other scenarios where all three measures are available, they contribute around 40%, 40% and 20% of the value, respectively.

Finally, campaign operation with periodical production of softwood and hardwood pulp is shown to be one way to enable these three flexibility measures and increase the value of the traded electricity. However, allowing flexibility also with respect to the time allocations of the different campaigns does not increase further the value of the traded electricity.

CRediT authorship contribution statement

Simon Ingvarsson: Conceptualization, Methodology, Visualization, Writing - original draft. **Mikael Odenberger:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Filip Johnsson:** Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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