Quantifying flexibility of industrial steam systems for ancillary services: a case study of an integrated pulp and paper mill

Xiadong Xu1, Muditha Abeysekera1, Christoph Gutschī2, Meysam Qadrdan1, Wenzl Markus3, Jianzhong Wu1, Nick Jenkins1
1 School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
2 cyberGRID GmbH & Co KG, 1190 Wien, Austria
3 Mondi Neusiedler, Theresienthalstraße 50, 3363, Ulmerfeld-Hausmening, Austria
E-mail: qadrdanm@cardiff.ac.uk

Abstract: Due to the increasing use of intermittent renewable generation, the power grid requires more flexible resources to balance supply and demand of electricity. Steam systems with turbine-generators, which are widely used in industries, can be operated flexibly to support the power grid. Yet, the available amount of flexibility of industrial steam systems is still not clearly quantified. This study presents the method to quantify electricity generation flexibility of a typical industrial steam system with a steam turbine-generator and process heat demands. The proposed method is introduced based on a real case of an integrated pulp and paper mill in Austria. An integrated mathematical model representing the combined electricity and steam system is developed to simulate the behaviour of the on-site energy system to quantify the potential flexibility provision. Flexibility is represented as the maximum upward and downward changes in the imported electricity from the public power grid. The results demonstrate that it is possible to aggregate the flexibility of the industrial facility as a lookup table. Also, the results reflect key factors that limit the flexibility at different operating points of the turbine-generator.

Notation

Variables

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| \( H_{\text{HP}} \) | enthalpy of the HP steam                        |
| \( H_{\text{MP}} \) | enthalpy of the MP steam                        |
| \( H_{\text{LP}} \) | enthalpy of the LP steam                        |
| \( H_{\text{FW}} \) | enthalpy of feedwater                           |
| \( \Delta H_{\text{HP, MP}} \) | enthalpy difference between HP and MP steam     |
| \( \Delta H_{\text{HP, LP}} \) | enthalpy difference between HP and LP steam     |
| \( P_{\text{E, Rated}} \) | rated electricity generation capacity of the turbine-generator |
| \( P_{\text{E, min}} \) | minimum electricity generation capacity of the turbine-generator |
| \( P_{\text{E, max}} \) | maximum electricity generation capacity of the turbine-generator |
| \( P_{\text{E, in}} \) | import electricity from the public grid         |
| \( P_{\text{E, out}} \) | export electricity to the public grid           |
| \( P_{\text{in}} \) | maximum value of \( P_{\text{E, out}} \)         |
| \( P_{\text{GB}} \) | natural gas consumption of the gas boiler       |
| \( P_{\text{RB}} \) | natural gas consumption of the recovery boiler  |
| \( P_{\text{in}} \) | import gas from the public grid                 |
| \( P_{\text{E, Rated}} \) | rated electricity generation capacity of the turbine-generator |
| \( P_{\text{E, min}} \) | minimum electricity generation capacity of the turbine-generator |
| \( P_{\text{el}} \) | total electricity load                          |
| \( P_{\text{f}} \) | amplitude of flexibility service                |
| \( P_{\text{r}} \) | time of response                                |
| \( T_{\text{d}} \) | duration of response                            |
| \( R_{\text{up}} \) | maximum ramp up rate of electricity generation of the steam system |
| \( R_{\text{down}} \) | maximum ramp down rate of electricity generation of the steam system |
| \( P_{\text{up}} \) | maximum increase of electricity generation      |
| \( P_{\text{down}} \) | maximum decrease of electricity generation      |
| \( E_{\text{up}} \) | amount of increasing energy use for flexibility provision |
| \( E_{\text{down}} \) | amount of decreasing energy use for flexibility provision |

Constants

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| \( \eta_{\text{GB}} \) | efficiency of the gas boiler                     |
| \( \eta_{\text{RB}} \) | efficiency of the recovery boiler                |
| \( \eta_{\text{T}} \) | electrical efficiency of the steam turbine-generator |
| \( \text{LHV}_{\text{NG}} \) | lower heating value of natural gas               |
| \( \text{LHV}_{\text{BL}} \) | lower heating value of the black liquor          |

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1 Introduction

Electric power systems around the world are going through a radical transformation dominated by a shift from using fossil fuel to intermittent renewable resources. More flexibility is required to adapt to sudden discrepancies between generation and demand [1].

To date, the energy industry typically provides flexibility on the ‘supply side’ by using reserve capacity and back-up generation. Building new power plants indicates high capital costs and long payback period. Thus, utilities are exploiting the flexibility of existing resources, such as demand response and energy storage. In [2], it is shown that using batteries for peak shaving and ancillary services can achieve profitability under the German market condition. In [3], it is shown that the flexibility of demand response from industrial loads can achieve more economic benefits in the long term than batteries under the Great Britain market condition for frequency response.

A key question in the flexibility study lies in how to define the flexibility and measure the level of system flexibility. In [4], flexibility is defined as ‘modifying generation and/or consumption patterns in a reaction to an external signal (such as a change in price) to provide a service within the energy system’. This concept is extended in [5–9]. In [5], system operating cost and reliability are considered in the flexibility metric. Considering uncertainties in the power grid, a probabilistic index is proposed to measure flexibility [6]. An envelope-based approach is proposed to quantify the flexibility of power systems’ resources for unit commitment and economic dispatch [7]. The determinants of flexibility are specified to time, actions, uncertainty, and cost [8]. The flexibility of energy storage and demand response is quantified for day-ahead scheduling in [9].

Industrial sites are potential candidates to provide flexibility to the power grid. It has been shown that electric loads in industries could provide flexibility to the power grid, such as spinning reserve [10] and frequency response [11]. Compared with electric loads, a more flexible resource is the steam system. Due to the characteristic of high energy density and the ability to deliver large quantities of heat at a constant temperature [12], steam is widely used to produce electrical, mechanical and thermal energies to production processes. Industrial steam systems can provide flexibility services to the power grid by changing the electricity generation of on-site steam turbines [13]. It is shown that industrial steam systems have the potential to provide frequency regulations [14, 15]. Yet, the provision of flexibility is often based on the operators’ experience and safety concerns, which are conservative and suboptimal. To acquire more profits, the maximum flexibility of the steam system needs to be quantified.

In an industrial steam system, steam, fuel, and electricity flows are tightly coupled by boilers, steam turbine-generators, and valves [16]. The regulation of electricity generation from the steam is limited by the capacities of all the equipment. Besides, variations of by-product fuel [17, 18], steam demand and electricity demand limit the maximum flexibility from the steam system. These limits have been taken into account in the optimisation of the steam system in previous work [19–21]. In [19], technical demand response potential of an integrated iron and steel plant is quantified without considering the limit of steam flow. In [20], the steam, electricity and by-product gas of an integrated iron and steel plant are optimised to achieve reasonable use of by-product fuel against time of use electricity price. In [21], the flexibility of the steam system of a refinery is studied against the day-ahead electricity market, which saves 68 million per year accounting for 1% of turnover.

One challenge in the flexibility analysis lies in the uncertainties of pressure and temperature as the steam demand changes. This change will affect the electricity generation from steam turbines and further change the available flexibility. A commonly used method to deal with the uncertainties is robust optimisation [22], which may lead to over conservative estimation of the flexibility and reduce the potential revenue from providing flexibility [23]. A trade-off between conservatism and maximum flexibility is thus required. In [24, 25], this trade-off is achieved by using data-driven robust optimisation with the regularisation parameter.

Yet, unlike making profits from energy saving, ancillary services have stricter requirements on the accuracy of adjusting electricity generation. For example, the secondary frequency response in Great Britain requires flexibility provider to achieve a full response in 30 s and sustain for 30 min [26]. As the steam demand varies, the maximum change of electricity generation from steam turbine may decrease [27] and further affect the steam system to maintain the flexibility provision. Moreover, the change of power system event is also a kind of uncertainty, which could result in the failure of flexibility provision. For facility owners, a higher amplitude of flexibility services indicates more profits but the higher risk in being penalised for failing in sustaining the services for the required duration.

To incorporate the requirements of ancillary services as well as constraints of the steam system, this paper conducts the following works: (i) Metrics of flexibility are defined, which include the speed of response, the amplitude of response, and the length of response. (ii) An integrated scheme is developed to help facility owners to quantify the technical flexibility of the steam system for various grid services. Although only an integrated pulp and paper mill is studied as an example of industrial steam systems, the proposed method can be applied to other industries with on-site steam generations.

The rest of the paper is organised as follows. Section 2 introduces the steam system studied in this paper. Section 3 presents how the steam system could provide flexibility to the power grid and how to measure the flexibility for different ancillary services. Section 4 discusses the model and flexibility quantification method of the integrated steam and electricity generation systems. Sections 5 and 6 present the case study by validating the model and revealing the flexibility of the integrated pulp and paper mill. Section 7 concludes the paper.

2 Integrated steam and electricity systems

2.1 Structure of the steam system

Fig. 1 presents a schematic diagram of the on-site energy supply system at a typical pulp and paper mill. The steam system consists of three pressure tiers: High Pressure (HP) steam; Medium Pressure (MP) steam; Low Pressure (LP) steam.

Two boilers produce HP steam. The gas boiler follows the variation of steam demand. The recovery boiler is fuelled by the black liquor from the paper production processes and supplemented by natural gas. Black liquor is a by-product of paper production processes. The natural gas consumption in the recovery boiler varies with the supply flow rate of black liquor. Steam generated by the recovery boiler depends on the paper production processes and is considered inflexible.
Steam and electricity generation system model

**Input**
- Steam demands
- Blow-off steam
- By-pass steam
- Steam flow of recovery boiler
- Black liquor flow
- Electricity demand
- Flexibility requirements

**Output**
- Electricity generation
- Imported electricity
- Imported gas
- Variations of by-pass steam
- Variation of blow-off steam
- Loss of feed-water

**Parameters**
- Water supply (temperature & pressure)
- Boiler (eficiency & capacity)
- Turbine (eficiency & capacity)
- Steam system (temperature & pressure)
- Reduction station capacity
- Blow-off and fresh water preparation limits

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Fig. 2 Model description of steam and electricity generation system of the pulp and paper mill

Paper Machine 3 (PM3), Paper Machine 4 (PM4), Evaporator (EVA), Pulp Machine (YZG) and other LP steam demands are connected to the LP steam system. Pulp machine recovery boiler is connected to the MP steam system and acquires steam to support its operation.

Steam demands (mostly at LP level) must always be served due to the production demand. A back-pressure steam turbine with MP steam extraction produces mechanical energy from the steam expansion process. Steam passing through the turbine is regulated by the steam demand for paper production processes. The turbine is coupled to a generator for on-site electricity generation. Any surplus/deficit between the on-site electricity generation and the electricity demand is balanced by the public power grid.

### 2.2 System model

Fig. 2 shows the structure of the model. The inputs to the model are steam demands at MP and LP levels, the flow rate of the blow-off steam, the flow rate of the by-pass steam, steam production of the recovery boiler, the flow rate of the black liquor, total electricity demand on-site, and flexibility requirements of the power grid. Technical characteristics of the steam system are obtained from design parameters and historical data and are pre-defined in the model. Outputs of the model are electricity generation on-site, imported electricity from the public power grid, variations of by-pass steam flows and natural gas consumed by the recovery boiler.

#### 2.2.1 Assumptions for modelling:

- pressure and heat losses in steam pipelines are neglected;
- transfer limits of steam pipelines are not considered;
- efficiencies of the steam turbine-generator and boilers are constant;
- energy demands are inflexible.

#### 2.2.2 Balance of steam demand and supply:

The balance of steam demand and supply at the MP steam system is expressed as

\[ \dot{m}_{D}^{D} + \dot{m}_{D}^{DF} = \dot{m}_{HP,MB} + \dot{m}_{HP,MP} \]  

where \( \dot{m}_{D}^{D} \) is the total LP steam demand, \( \dot{m}_{D}^{DF} \) is the steam flow rate via the blow-off valve at the LP steam system, t/h, \( \dot{m}_{HP,LP} \) is the steam flow rate via the turbine (HP→LP), \( \dot{m}_{HP,LP} \) is the by-pass steam flow rate (HP→LP).

The balance of steam demand and supply at the MP steam system is expressed as

\[ \dot{m}_{MP}^{D} = \dot{m}_{HP,MB} + \dot{m}_{HP,MP} \]  

where \( \dot{m}_{MP}^{D} \) is the MP steam demand. \( \dot{m}_{HP,MB} \) is the steam flow rate via the turbine (HP→MP). \( \dot{m}_{HP,MP} \) is the by-pass steam flow rate (HP→MP).

The balance of steam demand and supply at the HP steam system is expressed as

\[ \dot{m}_{HP}^{GB} + \dot{m}_{HP}^{RB} = \dot{m}_{HP,MB} + \dot{m}_{HP,LP} + \dot{m}_{HP,MP} \]  

where \( \dot{m}_{GB} \) is the steam flow rate of the gas boiler. \( \dot{m}_{RB} \) is the steam flow rate of the recovery boiler.

#### 2.2.3 Natural gas consumption:

As mentioned in Section 2, the steam is produced by the gas boiler and the recovery boiler. The energy consumption of the boilers depends on the difference between the enthalpy of feedwater \( H_{FW} \) and the enthalpy of steam produced by the boilers. In this paper, it is assumed that the temperature and pressure of the steam produced by the boilers are the same as the temperature and pressure of the HP system.

The natural gas consumption of the gas boiler \( \dot{m}_{NG}^{GB} \) only depends on the lower heating value (LHV) of natural gas \( LHV_{NG} \), which can be expressed as

\[ \dot{m}_{NG}^{GB} = \frac{\dot{m}_{NG}^{GB} \times (H_{HP} - H_{FW})}{\eta_{GB} \times LHV_{NG}} \]  

where \( H_{HP} \) is the enthalpy of the HP steam. \( \eta_{GB} \) is the efficiency of the gas boiler.

The recovery boiler consumes both natural gas and black liquor to heat up the water and produce steam to the HP system. Thus, the natural gas consumed by the recovery boiler \( \dot{m}_{NG}^{RB} \) depends on the amount of steam production and the input of black liquor. For a given steam flow rate \( \dot{m}_{RB}^{NNG} \), the natural gas consumption of the recovery boiler can be expressed as

\[ \dot{m}_{NNG}^{GB} = \frac{\dot{m}_{NG}^{RB} \times (H_{HP} - H_{FW}) - \dot{m}_{NG}^{RB} \times LHV_{BL}}{\eta_{GB} \times LHV_{NG}} \]  

where \( \dot{m}_{BL} \) is the mass flow rate of the black liquor. \( LHV_{BL} \) is the LHV of the black liquor. \( \eta_{GB} \) is the efficiency of the gas boiler.

#### 2.2.4 Electricity generation:

Referring to [25], the total electricity generation of the extraction back-pressure steam turbine...
is modelled as a combination of two separate back-pressure steam turbine-generation systems as follows:

- Steam flow to the MP system $m_{MP}^D$ passing through the turbine (HP→MP).
- Steam flow to the LP system including the blow-off steam $m_{LP}^D$ passing through the turbine (HP→LP).

Then the total electricity generation of the turbine $P^T$ is thus expressed as a combination of the mechanical power of the two back-pressure turbines multiplied by the electrical efficiency of the turbine-generator $\eta^T$.

$$ P^T = \eta^T \left( m_{MP}^D (H_{MP} - H_{MP}) + m_{LP}^D (H_{LP} - H_{LP}) \right) $$

(6)

where $\eta^T$ is the electrical efficiency of the steam turbine-generator. $H_{MP}$ is the enthalpy of the MP steam. $H_{LP}$ is the enthalpy of the LP steam. The enthalpy of steam is determined by temperature and pressure, which is mainly affected by the variation of steam demand.

Steam system production is a complex thermo-mechanical process. The relevant model and parameters for modelling this system are difficult to acquire [27]. Referring to the enthalpy-temperature diagram of steam, the enthalpy variation of steam generated by an HP boiler is mainly affected by the steam temperature. It is assumed that that the pressure of the steam is maintained at the designed level. A black-box model is employed to approximate the temperature of the steam in reference to the steam demand. The enthalpy of steam is then estimated based on the obtain temperature and pressure values at given steam demand levels.

3 Flexibility of industrial steam system

3.1 Provision of flexibility

This paper focuses on the technical flexibility of an industrial steam system, which is used for ensuring that the steam system is operated in a reasonable range. The flexibility is considered as the ability to change the level of import electricity without affecting steam supply to production facilities. This change is calculated with reference to the scheduled value.

In a typical steam system at an integrated pulp and paper mill, the following actions can be used for providing flexibility services.

3.1.1 Upward regulation: The upward regulation is provided via the following procedures in order:

i. If any by-pass steam flows are present (HP→MP or HP→LP), then the by-pass steam is reduced, so that the steam flow through the turbine increases.

ii. If there is no by-pass steam flow or the upward regulation requirement is not met by reducing the by-pass flow to zero, then the steam production of the gas boiler is increased.

iii. The additional steam production may create excess steam in the system that needs to be removed using the blow-off valve in the LP steam system. The blow-off steam would increase the cost of preparing freshwater to maintain the steam system operation.

3.1.2 Downward regulation: Downward regulation is provided by reducing on-site electricity generation via the following procedures in order:

- If blow-off steam exists, reduce the gas boiler steam production to minimise the blow-off steam and thereby the steam flow rate through the turbine is reduced.
- Open by-pass valves to re-route part of the steam flow outside of the turbine. The HP→LP by-pass valve is activated first due to its high efficiency.

3.2 Metric of flexibility

For a tendered flexibility service with requirements on the amplitude at $P_1$, the response time of $T_r$, and the duration of $T_d$, a system could provide this flexibility service if the following constraints are satisfied:

$$ P_{down} \leq P_1 \leq P_{up} $$

(7)

$$ \int_0^{T_r} R_{down} \, dt \leq P_1 \leq \int_0^{T_r} R_{up} \, dt $$

(8)

$$ E_{down} \leq \int_0^{T_d} P_1 \, dt \leq E_{up} $$

(9)

where $R_{up}$ and $R_{down}$ represent the maximum ramp up and ramp down rate of changing the imported electricity of the steam system, respectively. $P_{up}$ and $P_{down}$ represent the maximum decrease and increase of import electricity from the public power grid, respectively. $E_{up}$ and $E_{down}$ represent the amount of decreasing and increasing energy use of electricity for flexibility provision, respectively.

As mentioned earlier, the flexibility is provided by changing the turbine generation. Note that the ramp rate of the turbine-generator may vary at different levels of electricity outputs. To ensure that the flexibility can be delivered as requested, the minimum ramp up/down rate are chosen as the value of $R_{up}$ and $R_{down}$.

4 Flexibility quantification

In this section, a three-step method is proposed to quantify the flexibility of the steam system. In step I, the maximum instantaneous response of the steam system for changing electricity generation is obtained by optimising the steam-electricity flows. In step II, ramping limits of adjusting steam flows for electricity generation are taken into account to calibrate the amplitude of flexibility. In step III, the amount of flexibility will be estimated by considering the requirements for providing flexibility service, i.e. time to activate the service, and duration of the service.

4.1 Step I: maximum instantaneous response

The objective of the flexibility quantification is to obtain the maximum change of electricity generation of the steam turbine at a given operating point. This change is constrained by capacities and minimum operating points of valves, boilers, and the steam turbine.

The maximum upward regulation at time $t$, $P_{up}^T(t)$, is the maximum amount of imported electricity that the system can reduce from the current level of imported electricity. The maximum downward regulation at a given time $t$, $P_{down}^T(t)$, is defined as the maximum reduction of on-site electricity generation possible for the given system configuration.

Assume that the operating point of the system at a given time $t$ is as follows: the operating point of boilers $(m_{MP,bo}^{GB}, m_{LP,bo}^{GB})$, the operating point of turbine-generator $(P^T)$, by-pass valve setting $(m_{MP,MP}^{by}, m_{HP,LP}^{by})$, blow-off valve setting $(m_{LP}^{by})$, then the instantaneous flexibility of the steam system can be expressed as

$$ P_{up} = \max \left[ P_{up}^T(t) - P^T(t) \right] $$

(10)

$$ P_{down} = \min \left[ P_{down}^T(t) - P^T(t) \right] $$

(11)

subject to

(1)–(6)

$$ P^T + P_{up}^T = P_{down}^T $$

(12)

$$ P_{up}^T \leq P_{up}^T $$

(13)
where $P^e$ and $P^{en}$ represent the import electricity and its maximum value (purchased capacity from the public power grid), respectively. $P_{NG}^m$ represents the maximum import natural gas from the public gas grid. $P^T$ represents the electricity demand. $m_{rated}^{BF}$ is the maximum blow-off steam flow rate. $m_{rated}^{GB}$ is the rated steam production capacity of the gas boiler.

### 4.2 Step II: incorporating ramp limits

The ramping process of electricity generation from industrial steam systems is limited by the ramp rate of steam turbines as well as the ramp rate of the steam system that drives the turbine-generation system. The ramp rate of the steam system varies under different operating points.

The first limit of the electricity generation comes from the ramp rate of the steam turbine $R^{tur}$ as follows:

$$R^{down}_{tur} \leq R^{tur} \leq R^{up}_{tur}$$

where $R^{down}_{tur}$ and $R^{up}_{tur}$ represent ramp down and ramp up limits of the steam flow of the turbine, respectively.

During normal operations, the by-pass flow is operated at a level close to zero. The ramp up limit of the steam generation system $R^{gen}_{up}$ is then expressed as

$$R^{gen}_{up} = h^T \times \Delta H_{HP,LP} \times \min \{R^{up}_{GB}, R^{up}_{AP}\}$$

where $R^{up}_{up}$ is the ramp up limit of the steam flow produced by the gas boiler. As the upward regulation is achieved by blowing off steam at the LP system, so the only the maximum change of steam flow rate at LP system is considered. $\Delta H_{HP,LP} = H_{HP} - H_{LP}$.

The ramp down limit of the steam generation system $R^{gen}_{down}$ is expressed as

$$R^{gen}_{down} \geq h^T \times \Delta H_{HP,LP} \times \min \{R^{down}_{GB}, R^{down}_{AP}\}$$

where $R^{up}_{down}$ is the limit of increasing the by-pass flow.

### 4.3 Step III: incorporating maximum duration limits

As the steam demand varies, the steam flow through the turbine changes which results in different amplitudes of instantaneous flexibility. Yet, ancillary services require flexibility providers to sustain the change of turbine generation for a certain period.

### Table 1 Paramaters of the steam system at the paper mill

| Nominal capacity, t/h | Minimum flow rate, t/h | Efficiency |
|-----------------------|------------------------|------------|
| gas boiler 40         | 10                     | 0.93 (gas to heat) |
| recovery boiler 26    | 6.5                    | 0.88 (fuel to heat) |
| by-pass valve (HP->MP)| 25                     | 0          |
| by-pass valve (HP->LP)| 40                     | 0          |
| blow-off valve        | 50                     | —          |

Assume that the steam demand can be forecasted based on the production plan, then the maximum tendered flexibility can be expressed as

$$F^U(t, T_d) = \min_{h^T} \min \left[ P_{up}(t), R^{gen}_{up} T_d \right]$$

$$F^D(t, T_d) = \min_{h^T} \min \left[ P_{down}(t), R^{gen}_{down} T_d \right]$$

where $F^U$ and $F^D$ represent the maximum flexibility for upward and downward regulations with a duration of $T_d$ respectively.

### 5 Case study

In this section, the steam system model and the flexibility analysis method are applied to the steam system in Section 2. The model and flexibility analysis method are implemented in MATLAB 2019a with the support of the X Steam package [28].

The capacity of the turbine-generator is 10.5 MW with a minimum electricity output at 10% of the capacity. The electrical efficiency of the turbine-generator (enthalpy to electricity) is 0.9. The ramp rate of the turbine-generator is 3% of the rated capacity per minute. The ramp rates of valves are neglected. The water supplied to the boiler is assumed to be fixed at 104°C and 100 barg.

Details of the steam system are given in Table 1. The LHV is used in calculating the heat production of boilers (natural gas: 36.67 MJ/Nm$^3$, black liquor: 8061 MJ/t). The efficiency shown in Table 1 is obtained by using the LHV, which is larger than the typical efficiency of gas boilers obtained from higher heating value [29].

The real operation data of a winter day (23/01/2019, 1 min granularity) are presented. Fig. 3 shows the steam and electricity demands of the paper mill. The steam demand, particularly of consumer YZG (yellow area), changes evidently, which indicates the variation of the electricity generation from steam turbine-generator. As the electricity demand is relevantly stable throughout the 24 h.

Fig. 4a shows the pressure of the steam system. Steam pressure is stable in real operation and is assumed to be constant at 72 barg (HP steam), 12 barg (MP steam) and 3.5 barg (LP steam) for the simulation studies.

As shown in Fig. 4b, the temperature of the MP steam system is stable in real operation and is assumed 248.7°C in the model. The temperature of the HP steam system is shown to be variable, and it shows good correlation to the total steam demand. By correlating the steam demand data in and the corresponding HP steam temperature data in Fig. 4b, the temperature of the HP and LP steam systems at different demand levels are described by an artificial neural network model.

The supply flow rate of black liquor, the supply flow rate of natural gas and the steam produced by the recovery boiler are shown in Fig. 5. Due to the change of production processes, some variations exist in the black liquor flow.

### 6 Results and discussions

#### 6.1 Model validation

The model is used to simulate the system operation of the winter day. The model is validated by comparing the real operation data and the model outputs regarding the following indices: (i) imported electricity from the public power grid; (ii) on-site electricity generation; (iii) gas consumption of the gas boiler; and (iv) gas consumption of the recovery boiler.

A commonly used index, mean absolute percentage error (MAPE) is used to quantify the accuracy of the model. Comparison between the measured temperature and the NN model output of the HP system and the LP system are shown in Fig. 6. The results show that the model approximates the measured data at an accuracy of 1.09% for the temperature of HP system and an accuracy of 2.35% for the temperature of LP system within the variation zone of steam demand considered in this study.
Fig. 7a shows the comparison of the model output and the real operation data for the electricity generation of the steam turbine and imported electricity from the public power grid. Considering all the 24 h period, the MAPE of the electricity generation is 1.6%. The MAPE of the imported electricity from the public power grid is 3.5%. The model outputs for electricity generation and electricity import match closely with real operation data over the 24 h period.

Fig. 7b shows the comparison of model outputs and real operation data for natural gas consumption of the boilers. The MAPE of the natural gas consumption of the gas boiler is 4.2%. The MAPE of the natural gas consumption of the recovery boiler is 18.3%. The model estimates the natural gas consumption of the gas boiler with reasonable accuracy. For the recovery boiler, some mismatches exist, but the accuracy is still acceptable as shown in Fig. 7b.

6.2 Simulation of flexibility provision

In this case, the model is updated to incorporate the algorithms for providing flexibility services through upward and downward regulations. The winter day data profile is used for the demonstration.

The paper mill is participating in EU’s Electricity Balancing Market. Specifically, manual Frequency Restoration Reserve (mFRR) mechanism with an activation time of 15 min and a duration of 30 min is considered.

A downward regulation event requesting a 1 MW increase in the imported electricity is activated at 6:00 when the imported electricity is 4.8 MW. An upward regulation event requesting a 1 MW decrease in the imported electricity is activated at 18:00 when the imported electricity is 2.9 MW. Each event lasts for 30 min. Fig. 8 shows the flexibility request signals, the resulting impact on imported electricity, and the flexibility of imported electricity with a duration of 30 min. The results show that the imported electricity from the public power grid increases (compared to the case without flexibility provision) during the downward regulation event and decreases during the upward regulation event.

Variations of the imported electricity are caused by adjusting the electricity output of the turbine-generator, as shown in Fig. 9. It is observed that the downward regulation event at 6:00 reduces the power output of the turbine-generator for the 30 min period and the upward regulation event at 18:00 increases the power output of the turbine-generator for the 30 min period.
Fig. 10 shows the blow-off steam flow and the by-pass steam flow through the HP→LP by-pass valve. From 6:00 to 6:30, during the downward regulation event, the HP→LP by-pass valve is opened to increase the steam flow rate that by-passes the turbine which reduces the power output of the turbine-generator. From 18:00 to 18:30, during the upward regulation event, the steam production in the gas boiler is increased and the excess steam at the LP system is blown off to maintain the balance of steam supply and demand.

6.3 Quantification of flexibility for upward and downward regulations

The winter day data profile is used to quantify the maximum upward and downward regulations available at every time step. Fig. 12 shows the maximum upward regulation and downward regulation over the 24 h period. It is observed that the maximum downward regulation is larger than the maximum upward regulation in this case. Also, the flexibility bounds for mFRR are shown in Fig. 12. As expected the bounds are within the flexible regions.

Fig. 11 shows the factors that affect the maximum upward regulation at each time step in which the operating point of the turbine-generator is different. Limit U1 (resulted from unused electricity generation capacity of the turbine-generator), limit U2 (resulted from the maximum blow-off flow rate), and limit U3 (resulted from the unused capacity of the boiler) are also shown in Fig. 14. During the 24 h period, there are no by-pass steam flows, so the option to re-route the additional steam through the turbine-generator to increase electricity generation is not available. The maximum upward regulation is constrained by the unused boiler capacity in this case (see the green colour curve in Fig. 14). The unused capacity of the boiler depends on the difference between its full capacity and current operating point at every time step. As a result, the maximum upward regulation varies following the steam demand profile (see Fig. 12).

Fig. 14 shows the factors that affect the maximum downward regulation at each time step in which the operating point of the turbine-generator is different (the green line in Fig. 14). Since steam demands at MP and LP levels must always be served (and there is no blow-off steam in normal operation), downward regulation event as there is no change to steam production of the gas boiler. However, for the upward regulation, more steam needs to be generated by the gas boiler. Therefore, an increase in imported gas is observed during the upward regulation period (18:00–18:30).

Fig. 7 Comparison of simulation results and real operation data
(a) Electricity, (b) Natural gas

Fig. 8 Flexibility requirement signals and variations of import electricity

Fig. 9 Variations of the electricity output of the turbine-generator

Fig. 11 Variations of the imported gas from the gas grid
regulation is possible only by re-routing HP steam through the by-pass valves. Maximum downward regulation is constrained by limit D1 (resulted from the minimum stable generation of the turbine-generator) and limits D2 (resulted from maximum by-pass steam flows).

Fig. 15 shows the boundaries for upward and downward regulations calculated over the 24 h period in respect to the operating point of the turbine-generator.

The upward flexibility boundary is determined by limit U3. This limit results from the unused capacity of the gas boiler, which decreases linearly with the operating point of the turbine-generator. Some fluctuations were observed due to the variations of steam enthalpy at different temperatures.

The downward flexibility boundary includes two segments with different slopes. One segment is determined by limit D1 resulted from the minimum power output capacity of the turbine-generator. This segment increases linearly with the operating point of the turbine-generator.

Limit D2 determines the other segment. This limit results from rated capacities of the by-pass valves, existing blow-off steam and steam demands at LP and MP steam systems. Although capacities of the by-pass valves are fixed, the magnitude of downward flexibility increases slightly with the operating point of the turbine-generator. This is because the temperature of the steam produced by the boiler increases as the amount of steam production goes up. Note that the results are obtained based on the available data, so variations of the power output of the turbine-generator are limited.

Fig. 15 can be considered as a lookup table for the flexibility of the steam system, which can be estimated offline. Based on this table, aggregators can evaluate the flexibility of the turbine-generator at a given operating point, without acquiring detailed information of the industrial site. Thus, the table will reduce the burden of communication between aggregators and site owners. Moreover, online system optimisation that is normally used in conventional methods is not required, which will reduce the online calculation burden for flexibility quantification.

6.4 Benefit of providing flexibility

A simple financial analysis was conducted to provide an insight into the amount of revenue that can be obtained from participating in mFRR market. The revenue includes two main parts, namely capacity price and energy price. Capacity price refers to the money that the aggregator receives for maintaining the reserved power available all the time, regardless of its activation. Energy price refers to the money received for increasing or decreasing the electricity generation on request.

As shown in Fig. 15, 1 MW is used for mFRR positive (decreasing import electricity) and 2 MW is used for mFRR negative (increasing import electricity). Considering the pricing scheme for mFRR in Austria in 2019 [30], the paper mill can acquire €50,418/year as capacity price. If the paper mill is activated for providing the service, more profits can be acquired for energy price.

6.5 Impact of uncertainty on the model performance

In the steam system, uncertainty in steam demand or manufacturing process will affect the temperature and pressure of the steam, and further results in the variation of the maximum flexibility. As the accuracy of the model plays a key role in the flexibility analysis result. This case compares the model output with operational data of typical weeks of four seasons from the paper mill to study the impact of uncertainty. It can be seen in Table 2 that the model has high accuracy at different seasons.
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