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Methodology to analyze combined heat and power plant operation considering electricity reserve market opportunities

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ABSTRACT

This paper presents a methodology to promote the operation of combined heat and power (CHP) power plant in the liberalized energy markets. The methodology considers a combination of marketplaces available to the power plant for its end products heat and electrical power, with a special reference to electricity reserve market opportunities. A result of the paper is a daily operation sequence to analyze the hourly operation in the heat and electricity markets. The proposed methodology is tested with price data of the respective energy and power markets between years 2013 and 2015.

1. Introduction

Electrical power markets are facing major changes in many countries. Reasons for this are the rapid increase [1] in renewable power generation boosted by green energy policies [2], subsidies for the renewables, and changes in people's attitudes and electricity consumption habits [3].

The increasing amount of solar and wind power production [2,4,5], typically leads to a situation where the power balance may fluctuate significantly over a short period of time. This can be problematic for the electrical power system if the power production or demand cannot be controlled. Thus, the electrical system has to contain reserve power capacity and/or demand response, which is able to respond to a deficiency in power production or overproduction. Power balancing can be arranged by using power plants that can be adjusted according to the power demand. Moreover, to be able to quickly increase the power production, the power plant cannot initially be driven with full electrical power. These conditions can be met by CHP plants, which have an ability to increase flexibility, for instance, by controlling the power-to-heat ratio. Flexible power production is essential from the perspective of power system balancing [6].

The output power of the CHP power plants is typically determined by the heat demand in the heat system [7], which can be, for instance, a district heating (DH) network or a large-scale industrial operator. Thus, the electricity production is determined based on the boiler power required for the heat production. It would also be possible to operate the power plant based on the electricity production, but the present low electricity wholesale price does not encourage this operation.

Optimization of CHP plant operation has been described for instance in Refs. [5,8,9]. These research reports discuss the optimal operation in liberalized power markets. However, the studies do not consider short-term electricity markets such as intraday market or electricity reserve markets. In Refs. [10,11], the opportunity to use a CHP power plant in reserve market operation is considered, and thus, these papers serve as an introduction to this paper.

In this paper, the objective is to develop a methodology to analyze the operation of a CHP power plant in liberalized energy markets covering the heat energy market, the day-ahead electricity market, the intraday electricity market, and the electricity reserve power markets.

2. Electrical energy system

The basic function of an electrical energy system is to produce and deliver electricity to electricity end-users without interruptions and with good quality. The electrical power system has to be operated so that production and demand are always in balance to keep the system frequency stable at the desired value, such as 50 Hz. Therefore, it would be beneficial for the system if both the production and demand were stable. In reality, demand is not

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stable, and thus, production has to follow the demand. If production and demand are in imbalance, the system frequency starts to decrease or increase depending on the imbalance. If demand is higher than production, the frequency starts to fall. The opposite situation, when the production is higher, indicates a rising frequency. When the change in frequency reaches a certain level, the stability of the system is lost and the system will collapse causing a blackout. Therefore, the system has to contain regulating production capacity to ensure stability of the system. An example of the system frequency is presented in Fig. 1.

The figure shows a dead band, which is the frequency band where the frequency is not regulated in the Nordic countries [12]. It can be seen that the frequency has to be regulated many times within an hour. The same issue is illustrated for the years 2008–2016 in Table 1, which presents the percentage of hours in a year during which the frequency deviates from the frequency limits. For instance, in the year 2014, 81% of the hours contained an instant when the frequency was below 49.95 Hz. Similarly, 82% of the hours contained an instant when the frequency was above 50.05 Hz. Further, it seems that the percentage of instants when the frequency falls outside the limits has increased year by year. For instance, when the frequency fell below 49.9 Hz in 23% of the hours in 2008, the percentage was 33% in 2015.

The frequency statistics indicate that the power system is under continuous control, and thus, the frequency containment reserves play an important role in system balancing. As the statistics show, the role of reserves is increasing even further in the future.

3. Energy markets

Energy markets can be divided into heat and electrical energy markets. The heat energy market is typically a local and limited regional district heating system, whereas electrical energy markets can be cross-border multinational markets.

3.1. District heat market

Local district heat markets are often operated by a dominant operator, which usually owns both the heat production capacity and the district heating network. Thus, the market is often inflexible, and the consumer prices are closely related to the pricing of the dominant operator. However, pricing is not free of regulations. For instance, according to the Finnish competition legislation [13], the district heating operator is in the dominant market position and the abuse of the dominant market position is prohibited. For the DH industry this means that prices are reasonable and cost-reflective, similar customers are treated equally, and different products are not pulled together in the total energy delivery.

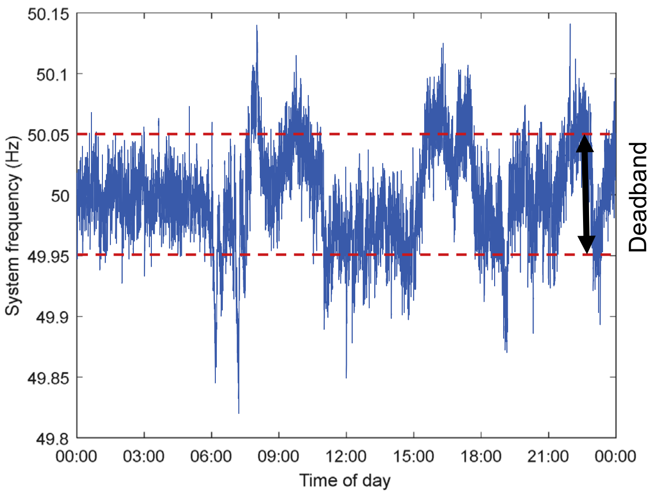

Fig. 1. Frequency of the electrical power system in the Nordic countries on 4 February 2013.

Table 1
Hourly deviation from the frequency limits between the years 2008 and 2016. The statistics of 2016 are for the period of January–July.

	$f < 49.5$ Hz	$f < 49.9$ Hz	$f < 49.95$ Hz	$f > 50.05$ Hz
2008	0%	23%	74%	75%
2009	0%	26%	75%	75%
2010	0%	29%	78%	77%
2011	0%	31%	81%	78%
2012	0%	31%	79%	79%
2013	0%	31%	82%	80%
2014	0%	30%	81%	82%
2015	0%	33%	84%	83%
2016	0%	41%	85%	85%

3.2. Electrical energy markets

Electrical energy markets in Europe have evolved rapidly since their opening in the 1990s [14]– [15]. The markets are divided into segments. In the Nordic Electricity markets, the main wholesale market is the day-ahead market Elspot, which defines the hourly prices for the produced and consumed energy. The intraday market supplements the day-ahead market by giving an opportunity, for instance, to fix the energy balance of the market actor.

In addition to the day-ahead and intraday markets, the electricity markets contain electricity reserve markets, which play a key role in stabilizing the system production and demand. Electricity reserve markets, in particular, are interesting from the perspective of CHP operators, because in some reserve market products the compensation is based on power, not on energy.

3.2.1. Day-ahead markets

The day-ahead market Elspot is the main wholesale market in the Nordic power market Nord Pool. The trade in the market closes on the previous day before the supply at 1:00 p.m. East European Time (EET). Nord Pool publishes the prices around 2:00 p.m. [16]–[17]. The day-ahead market is also the main market for the CHP operators.

Over the past few years, hourly Elspot prices have typically varied between 10 and 100 €/MWh,h, even though prices of single hours may have been lower or significantly higher. However, the statistics show that prices have been relatively low since 2011; this can be seen in Fig. 2. This is a challenge for the electricity producers, including the CHP operators, because a significant proportion of their income is based on electricity, the production cost of which can be close to the average market price or even less.

3.2.2. Intraday markets

The intraday market provides an option for the market parties to adjust their power balance if required. In Nord Pool, the intraday market is a continuous market, where the trading ends each day 1 h before the delivery [19]. The trade unit is similar (€/MWh,h) as in the day-ahead market. The difference between the day-ahead and intraday markets in Nord Pool is that when all the hourly trading in the day-ahead market gets the same price, in the intraday market all sales are independent and agreed with the sale parties. From the perspective of CHP operators, the intraday market provides an option to balance their production.

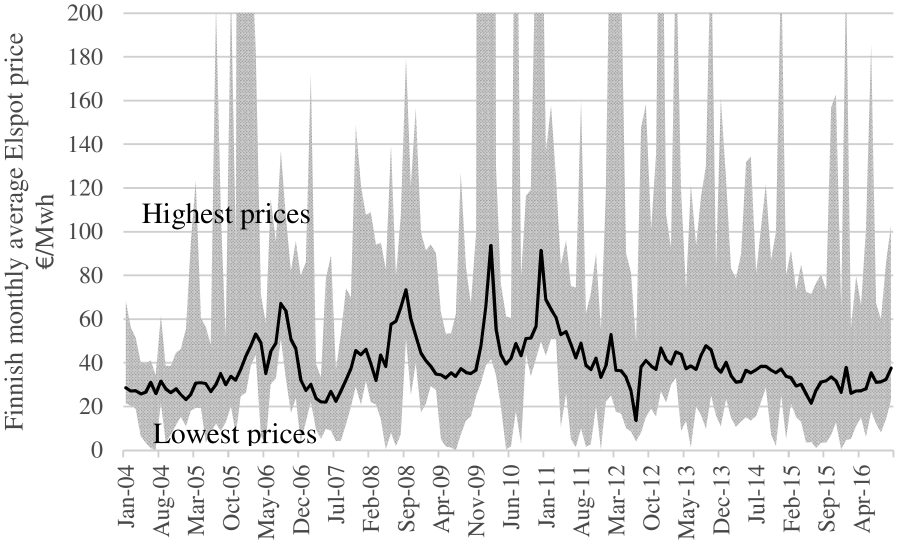

Fig. 2. Monthly average Elspot prices with the variation range of prices in the Finnish price area between 2004 and 2016 [18].

3.2.3. Reserve markets

Electricity reserves play a key role in stabilizing the power system. They ensure that the frequency of the system remains within a stable band. In the Nordic electrical power system, the obligations to maintain reserves are divided between the Nordic transmission system operators (TSO). For instance, in Finland the reserve market is arranged by the Finnish TSO, Fingrid. The reserve products comprise Frequency Containment Reserve for normal operation (FCR-N) and disturbances (FCR-D), automatic (FRR-A), manual (FRR-M) Frequency Restoration Reserves, and Replacement Reserve (RR) [20].

In Finland, the frequency containment is carried out with the FCR-N and the FCR-D, which are in the focus of this study. They are responsible to react if the frequency deviates from the normal operation band. The Frequency Restoration Reserves (FRR) are taken into use if the Frequency Containment Reserves (FCR) have to be restored for use. The commitment of Finland to maintain the FCR-N is 140 MW and 220–265 MW for the FCR-D. The market of the both reserves closes at 5:00 p.m. East European time (EET) [12].

The hourly mean prices and the volume of accepted capacity offers in both the FCR-N and FCR-D markets between years 2011 and 2016 are presented in Table 2 and Table 3. The statistics show that the prices can fluctuate considerably between the years, but also within the years. The standard deviation is relatively high, which is a consequence of the limited market size. On some hours the price is zero because the market is saturated, while on the following hours the price can be more than double compared with the mean price. Thus, hourly reserve markets provide a chance for CHP operators to search for new business opportunities.

3.2.3.1. Participation in the FCR-N market. The Frequency Containment Reserve for normal operation is the first reserve that reacts when the frequency crosses the limits of the normal frequency band, which is between 49.95 Hz and 50.05 Hz. Thus, this reserve has to be available for both electrical power up- and down-regulation, which may be challenging for the CHP operators. The operation droop is determined in the reserve agreement. The size of the bids to these markets has been limited so that one operator cannot cover the whole market, which automatically spreads the market between several actors. The highest bid for the FCR-N is 5 MW and the smallest bid is 0.1 MW [12].

3.2.3.2. Participation in FCR-D market. The Frequency Containment Reserve for disturbances is reserved for sudden occurrences such as disconnection of large power plant units, which would threaten the stability of the electrical system. The FCR-D reacts if the frequency decreases below 49.9 Hz. All the reserves have to be in operation if the frequency reaches 49.5 Hz. This reserve is used only for electrical power up-regulation. The highest bid for the FCR-D is 10 MW and the smallest bid is 1 MW [12].

4. CHP power plant operation

The combined heat and power plants are typically operated primarily to cover the heat demand of the system. The system can be, for instance, a district heating system or an industrial process. The benefit of the CHP process is the higher efficiency (typically 60%–90%) [22]– [23] compared with separate heat and electricity production [24]; in separate electricity production, the efficiency is

Table 2
Realized mean and standard deviation of hourly transaction prices and accepted volumes in the FCR-N markets between years 2011 and 2016. The statistics of year 2016 are for the period of January–September [21].

	Mean value	St. dev.	Mean value	St. dev.
	FCR-N price (€/MW,h)	FCR-N Price (€/MW,h)	FCR-N quantity (MW)	FCR-N quantity (MW)
2011	14.9	45.9	2.0	5.3
2012	30.4	56.7	7.2	9.7
2013	36.3	46.3	10.1	11.4
2014	31.9	35.8	14.7	15.5
2015	22.3	21.6	13.8	11.4
2016	17.2	18.9	10.1	11.2

Table 3
Realized mean and standard deviation of hourly transaction prices and accepted volumes in the FCR-D markets between years 2011 and 2016. The statistics of year 2016 are for the period of January–September [21].

	Mean value	St. dev.	Mean value	St. dev.
	FCR-D price (€/MW,h)	FCR-D price (€/MW,h)	FCR-D quantity (MW)	FCR-D quantity (MW)
2011	16.9	50.0	6.5	7.8
2012	6.0	30.7	2.1	5.1
2013	23.4	49.9	11.1	12.4
2014	8.0	16.8	6.4	10.1
2015	14.4	31.5	12.1	12.6
2016	6.4	14.7	5.8	11.8

30%–45%, depending on the production type of the power plant. For instance, the average efficiency of coal- and oil-fired power plants is around 36%, and a gas-fired power plant may reach an efficiency of 46% [25], which is significantly lower than the efficiency of a CHP plant.

A precondition of CHP produced to participate in the electricity reserve market is to have a capability to adjust the electricity power production in a few seconds or minutes. Typically, this is possible by adjusting the pressure regulators (reduction valves) of the turbine steam bypass [11]. The turbine bypass is presented in Fig. 3, which shows an example of a small-scale CHP plant, where the steam is conducted through a pressure reducing valve (PRV) to a condenser, where the heat is delivered for instance to a district heating network.

4.1. Heat demand

Often, in CHP production, the electricity production adapts to the heat production so that the efficiency of the process is maximized. Often when the heat demand is at lowest, the power plants are in annual revision. In the Nordic countries, where the peak demand occurs in wintertime, the CHP power plants are shut down in summer. This means that the power plants could be used to offer reserve power to electricity system services for most of the year. Examples of annual and daily heat demand in the Nordic environment are presented in Figs. 4 and 5, which show the statistics of a Swedish district heating system. It can be observed that the operation time with a relatively high power is from nine to ten months in a year.

Heat demand of society is highly dependent on outdoor temperature. Another factor that affects the heat demand is the daily living routines. Often, there is a peak in the heating system in the morning between 7:00 a.m. and 9:00 a.m.

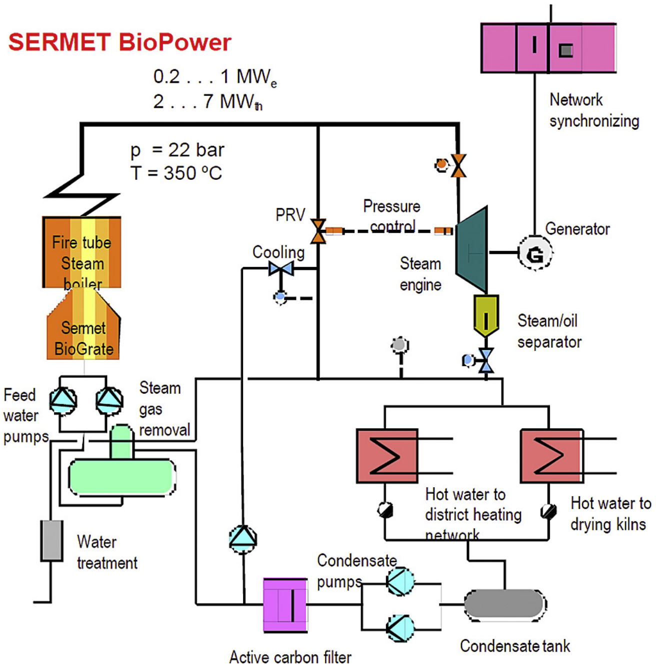

Fig. 3. An example graph of a small scale CHP plant [26].

4.2. District heating network

District heating network is the delivery route for the heat produced in CHP plants. A distinctive feature of the district heating network, when compared with the electricity distribution network, is its capacity to store energy as well as a separate thermal energy storage [7]. In the district heating system, because of the large amount of water, the time constants are typically long, meaning that the system can store energy [28]. Thus, the district heating system can be used as a buffer to balance fluctuation in heat production, as has been proposed for instance in Ref. [29]. The capability of the DH network to store energy can be used to balance the production of the CHP plant. An example of a Finnish district heating system shows that the storage capacity can be even 30% of the annual peak load hour capacity [30]. Thus, the storage capacity of the DH network provides an advantage for the CHP operator to optimize electricity production, for instance to enable operation in the FCR markets. Another option to provide flexibility in the energy system operation is to increase demand response in DH networks [31]– [32].

5. Methodology and formulation

In the paper, a methodology is proposed to analyze the feasibility of the CHP process when it is participating in the electricity reserve markets. The study focuses on CHP plants, the electrical power production of which can be adjusted by bypassing the turbine by a pressure regulator (reduction valve) [10]. This is a typical feature in CHP power plants of all sizes. However, because the reserve market instructions indicate that the allowed reserve market offers are limited to 5 MW in the FCR-N market and 10 MW in the FCR-D market, the participation may be more interesting for small- and medium-size operators at least in Finnish electricity markets. This provides an opportunity to participate in electricity reserve markets, which, again, opens up new business opportunities. The reserve market operation of the CHP power plant is illustrated in Fig. 6.

Fig. 6 presents two operation scenarios for a CHP plant. In traditional operation, the required heat energy is produced to supply heat to consumers, and the maximum available electrical power is sold to electricity markets (day-ahead market). In the case of reserve market participation, the normal operation mode is determined so that the operation profit is maximized. Often, the

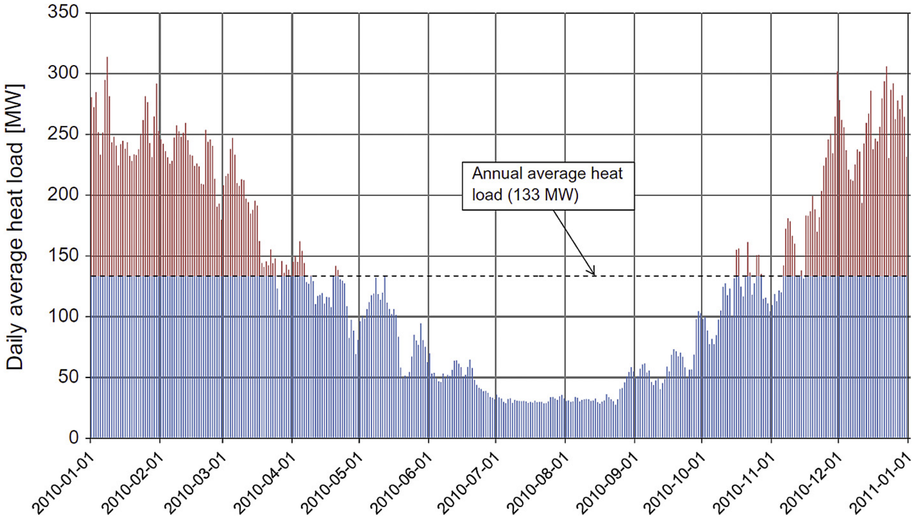

Fig. 4. Heat demand in a Swedish district heating system [27].

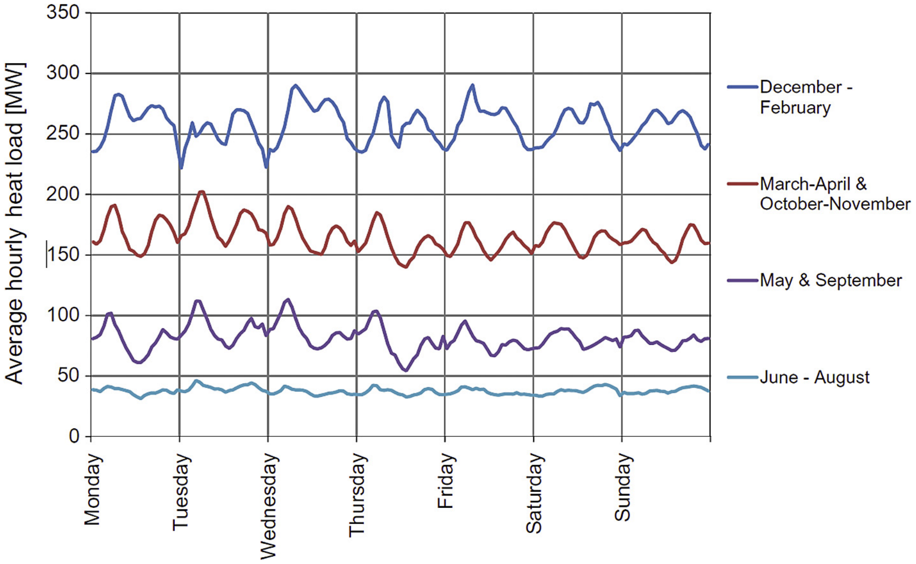

Fig. 5. Daily heat load variation for four seasons in a year in a Swedish district heating system [27].

maximum profit is achieved when the reserve market capacity is maximized. For instance, normal operation, where the system frequency is between 49.95 and 50.05 Hz, means for FCR-N participation that 50% of electricity capacity is produced, and thus, sold to the day-ahead market. This proportion provides the maximum electricity up- and down-regulation capacity for the producer to be sold to the reserve market. In this case, the operator increases or decreases the electricity output depending on the system frequency. Thus, the electricity output may vary between 0% and 100% of the maximum electricity output. However, the full reserve capacity, either 0% or 100% of electricity production, is not implemented in each hour. For instance in 2016, the frequency fell below 49.9 Hz in 41% of the hours.

In addition, when electricity production is regulated by using a reduction valve, the heat production is increased. This means that the operator can sell the normal heat production capacity increased by steam that bypasses the turbine (in normal operation, 50% of the maximum electrical power output). This can be explained by an example where the maximum electricity capacity of a CHP plant is 3 MW, and similarly, the heat production capacity is 7 MW. If 50% of the electricity capacity is reserved for the frequency reserve, only 1.5 MW of electricity power production can be sold to the day-ahead market. The rest, 1.5 MW, can be sold to the FCR-N reserve market. Now, the heat production capacity is not the nominal 7 MW, because the reserve market participation (steam bypass by a pressure regulator) increases the heat production capacity by 1.5 MW, meaning 8.5 MW of the heat production capacity, which can be sold to the heat market. Thus, the study shows that the CHP operator can, at least to some degree, sell the boiler capacity twice: a proportion of the electricity production capacity is sold first in the frequency containment reserve market (capacity market €/MW), and at the same time, the heat energy produced with the same capacity is sold to the heat market. This may cause challenges in a situation where the system frequency lies below the nominal point (50 Hz) for a long time (hours), causing a need for electrical power up-regulation. This may lead to a shortage in the heat delivery. However, the frequency statistics indicate that this is not a typical situation.

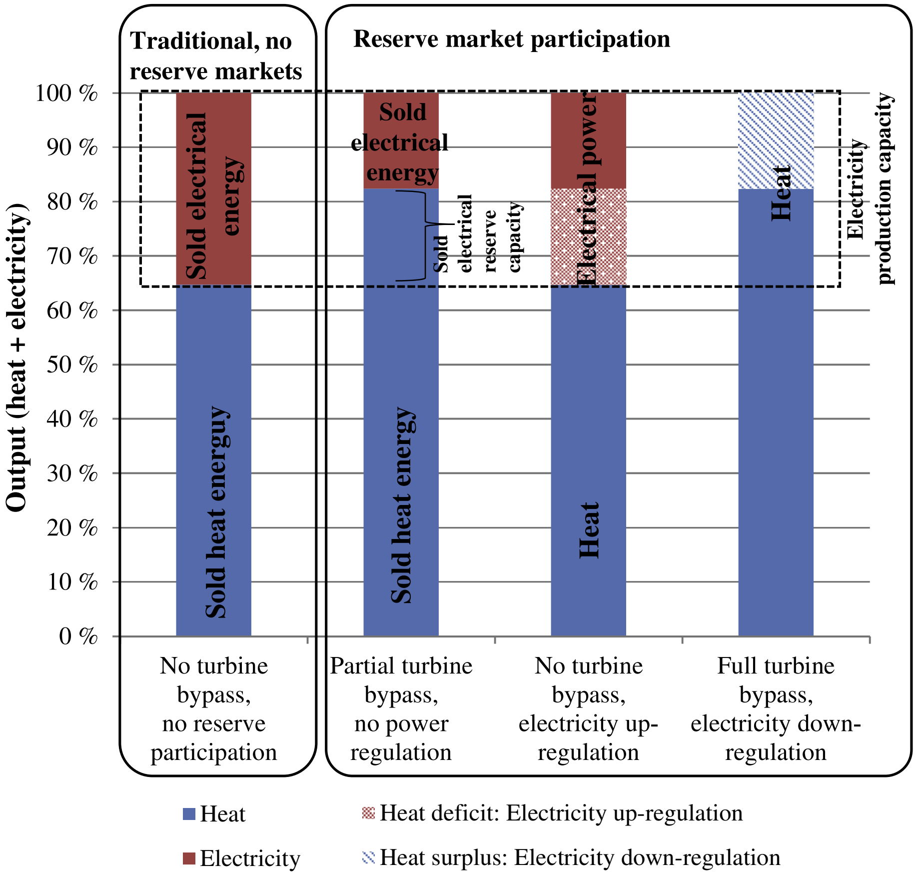

Fig. 6. Operation scenarios for an example CHP plant. 1) Traditional operation without participation in the electrical power reserve market, which makes it possible to produce electricity at the maximum power-to-heat ratio. 2) Participation in the reserve markets, when the power-to-heat ratio is adjusted so that the electrical power output is limited by a partial turbine bypass in normal operation [10].

5.1. Formulation

The profitability of the CHP process is formulated as follows. The objective is to maximize the profit of operation over the power plant lifetime

$$Profit = Max \int (Incomes(t) - Costs(t))dt, \tag{1}$$

where incomes are the sum of heat and electricity sales and costs are the sum of CHP power plant costs in a moment t. However, when considering participation in the hourly reserve markets, the time window of the optimization is 24 h instead of the lifetime. The incomes are

$$Incomes(t) = D_{\mathrm{Heat}}(t) + D_{\mathrm{Electricity}}(t). \tag{2}$$

The heat income D_{Heat} results from the delivered heat energy, and the electricity incomes $D_{\mathrm{electricity}}$ are a sum of all electricity market sales taking into account the day-ahead market $D_{\mathrm{Day\text{-}ahead}}$, the intraday market D_{intraday}, and the electricity reserve market sales $D_{\mathrm{FCR\text{-}N}}$ and $D_{\mathrm{FCR\text{-}D}}$

$$D_{\mathrm{Electricity}}(t) = D_{\mathrm{Day-ahead}}(t) + D_{\mathrm{Intraday}}(t) + D_{\mathrm{FCR-N}}(t) + D_{\mathrm{FCR-D}}(t). \tag{3}$$

The costs of the CHP power plant consist of the investment $C_{\mathrm{Investments}}$ and operation costs $C_{\mathrm{Operation}}$

$$Costs(t) = C_{\mathrm{Investsment}}(t) + C_{\mathrm{Operation}}(t). \tag{4}$$

However, even though the investment costs represent a significant part of the lifetime costs, in the daily optimization (on the timescale of a day), the investment costs are not taken into account. Thus, only the variable costs are included.

The operation costs can be divided into three segments: personnel $C_{\mathrm{Personnel}}$, maintenance $C_{\mathrm{Maintenance}}$, and fuel costs C_{Fuel}

$$C_{\mathrm{Operation}}(t) = C_{\mathrm{Personnel}}(t) + C_{\mathrm{Maintenance}}(t) + C_{\mathrm{Fuel}}(t). \tag{5}$$

The long-term operation plan is carried out in a separate strategy process, which determines whether the power plant is in production. Thus, the personnel costs are not controllable in the optimization over a 24 h time window. Consequently, the majority of the variable costs are based on fuel costs, which can be divided into three categories: heat production $C_{\mathrm{Heat,fuel}}$, electricity production $C_{\mathrm{Electricity,fuel}}$, and fuel discharge loss $C_{\mathrm{Fuel,discharge}}$. The discharge loss depends on the fuel type. For instance, in the case of biomass often used as a fuel in CHP plants, the discharge loss (decay of the fuel) can be significant, if the fuel is stored for a long time before use

$$C_{\mathrm{Fuel}}(t) = C_{\mathrm{Heat,fuel}}(t) + C_{\mathrm{Electricity,fuel}}(t) + C_{\mathrm{Fuel,discharge}}(t). \tag{6}$$

5.2. *Daily market offer methodology*

The methodology considers a variety of energy markets in the process, with the focus on the heat energy market, the electricity day-ahead market, the frequency containment reserve markets, and the electricity intraday market. This combination provides a wide scale of different options to optimize the profitability of the CHP operation. Because the reserve market is a capacity market, the CHP operator can sell the output power capacity and the produced energy separately. In this case, the power capacity is sold in the electricity reserve markets and the energy in the heat market.

Fig. 7 presents an electricity market offer sequence, which describes the actions that the operator takes routinely each day. Within a day, each hour has to be processed separately. Closing of the different markets is scheduled so that it is possible to amend the daily operation strategy with complementary markets. For instance, the reserve market offers are dependent on the results of day-ahead market offers. If the offers are not accepted, the intended strategy to participate for instance in the day-ahead market and the FCR-N market has to be adjusted accordingly. In this case, the operator can offer the capacity to the FCR-D market, and if not accepted, finally to the intraday market.

The CHP operator's daily electricity market participation sequence is illustrated in more detail in Fig. 8, where two alternative offer sequences, Part A and Part B, are presented.

Part A is the sequence for a situation where the boiler is operated with a full power, indicating high heat demand. If the heat demand can be satisfied with the nominal heat production capacity, electricity is typically produced by the nominal output with the maximum 100% output power at a low electricity production cost. If the heat demand is higher than the nominal heat output, the proportion of the steam that is normally led to the turbine is now condensed to heat, providing a higher heat output.

Part B is the sequence for a case where the boiler is normally in partial load operation because the heat demand is lower than the production capacity. In this case, the sequence is split into two parallel offer routes, the first of which describes the CHP plant operation with optimal efficiency, that is, a low electricity production cost for X_2% of the electricity capacity. The second route should be taken simultaneously with the previous one. Now, because the system heat demand is already met and the electrical power production plan is optimized in the CHP plant, the rest Y% of the electricity production capacity can only be produced with a high electricity production cost. The high electricity production cost is a consequence of the surplus heat that cannot be supplied to the heat network but has to be condensed to waste. Thus, the produced electricity has a higher marginal cost, and it can only be offered to the electricity market with a higher price.

Usually, maximum benefits can be obtained when the proportion of capacity market offers is maximized. In the FCR-N market this means that the suitable offer size is 50% of the maximum electricity production capacity of the hour under consideration, because the capacity has to be bidirectional. Thus, at first, 50% of the capacity is offered to the day-ahead market, and if the offer is

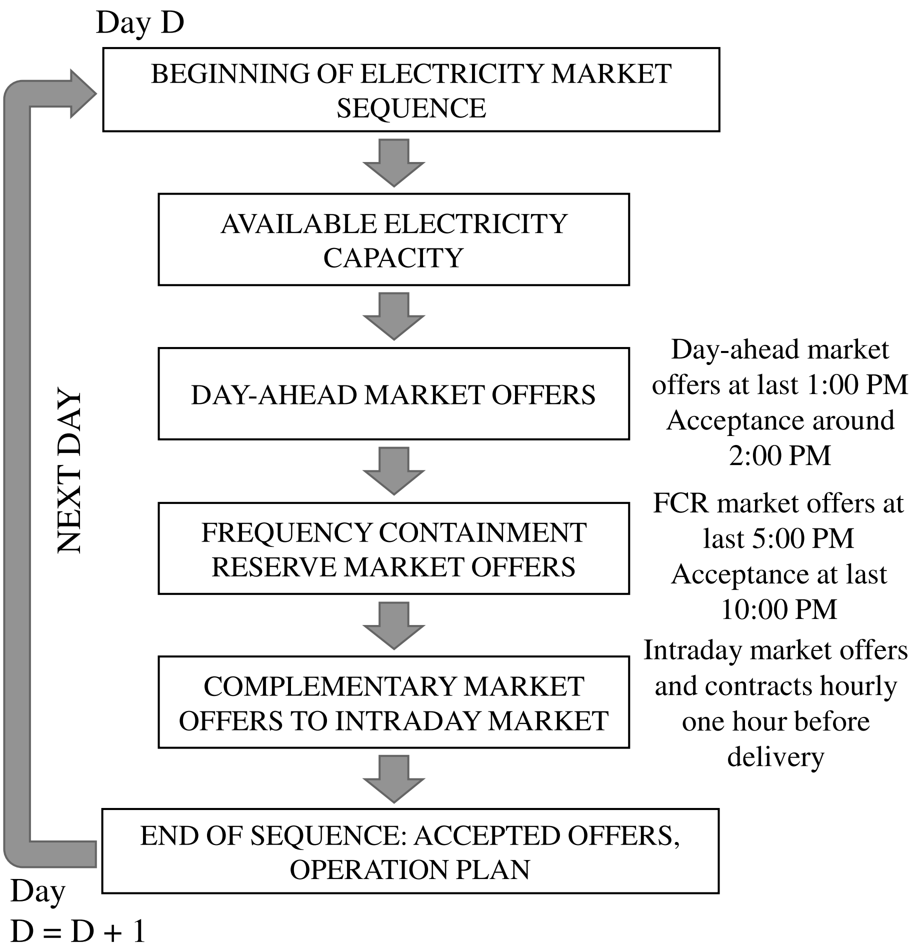

Fig. 7. Electricity market offer sequence for each day. The time stamps are in EET.

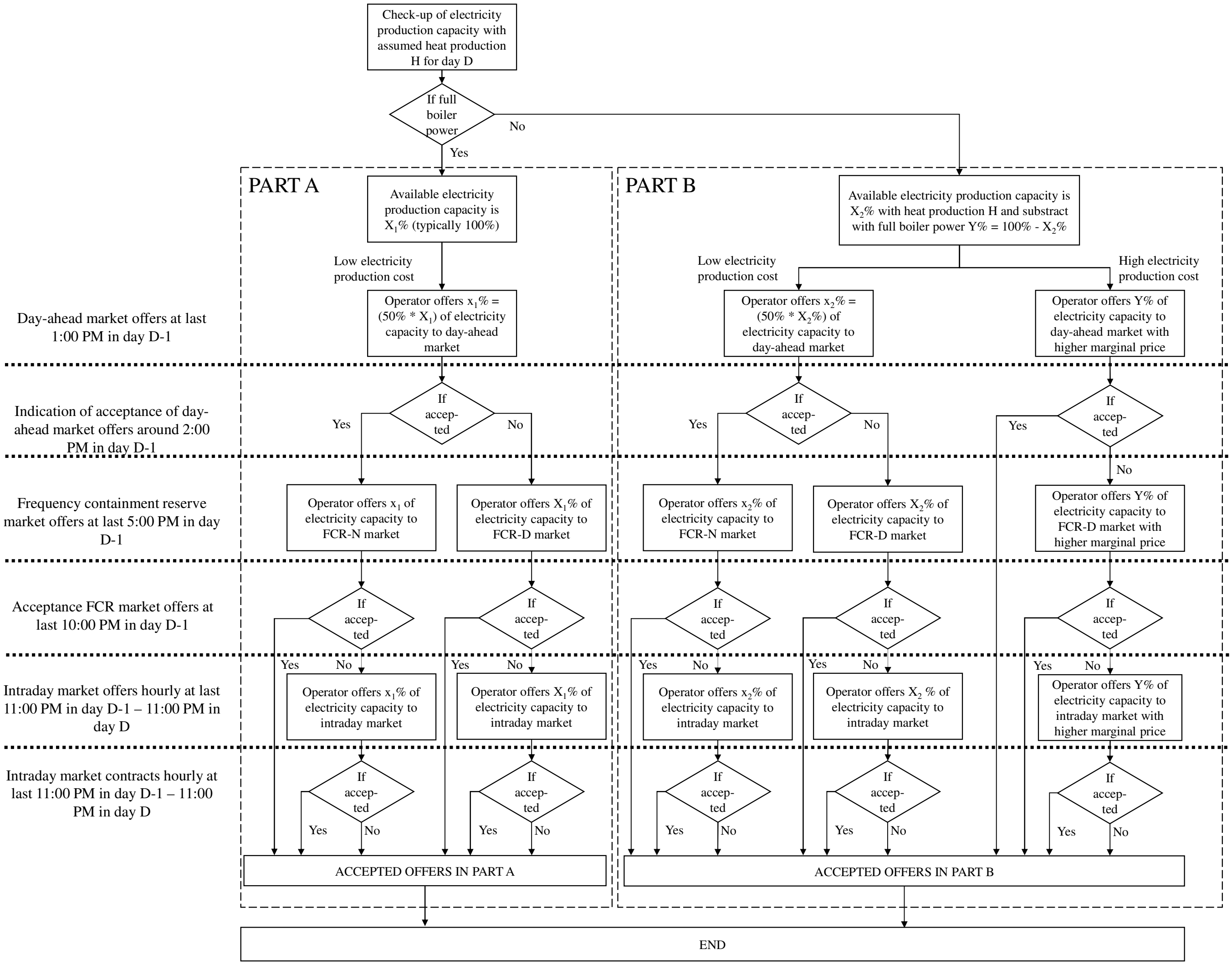

Fig. 8. One-day electricity market offer sequence of a CHP operator in the case where the heat energy balance does not have to be corrected. The time stamps are in EET.

accepted, the CHP operator is free to offer 50% of the capacity to the FCR-N market, where both the up- and down-regulation of electrical power is required. This is an easy task when the heat demand is high, and the power plant is operated with full boiler power (Part A in Fig. 8). If the day-ahead market offer is not accepted, the operator cannot offer capacity to the FCR-N market, because the electricity down-regulation is not possible. However, the operator can offer the whole electricity production capacity to the FCR-D market, where only the electricity up-regulation is required. If the reserve market offers are not accepted, the operator can still offer available capacity to the intraday market, which closes separately for each hour 1 h before the delivery hour.

A special case of the full boiler operation (Part A) occurs when the nominal heat production capacity does not meet the heat demand. Thus, an option is that the power plant is operated in the partial turbine bypass mode to produce extra heat in the heat system, decreasing the available electricity output capacity by Z%. In this case, the offer sequence contains, in addition to normal Part A, an extra offer block not described in Fig. 8. Because the turbine bypass is already used in the operation, the operator can offer Z% of the nominal electricity production capacity (decreased electricity production capacity in the turbine bypass) to the FCR-D market. If the offer is accepted, the electricity up-regulation may cause a shortage in heat delivery resulting in a decrease in the water temperature in the district heating network. This can be corrected in the next hours by raising the heat production by increasing the output of the boiler or by adjusting the turbine bypass. If the offer is not accepted, this does not have an effect on the operation.

When the heat demand is limited, also the electrical power output is limited (Part B in Fig. 8). Hence, the FCR-N capacity is reduced in the optimal efficiency point. The electrical power capacity can be increased by increasing the boiler power, but this means that the produced surplus heat energy has to be condensed, which reduces the overall efficiency of the process. Thus, the extra electricity production (Y % in Fig. 8) gets a higher unit price, which has an effect on the price of the market offer. In part B, the offer sequence is split into two parallel chains, which both have to be gone through. It would be beneficial for the operator to make two separate offers to the markets: an offer with a lower production marginal cost and another offer with a relatively high production cost, because the electricity production can only be increased by wasting part of the heat production. The rest of the offer sequence of part B is quite similar to part A.

As a result, the CHP operator gets an hourly operation plan for the power plant in the selected markets; in this case, the electricity day-ahead, reserve, and intraday markets, respectively. The flowchart of Fig. 8 does not take into account the upkeep costs of the power plant. Typically, the power plant has a seasonal operation plan providing information of whether the plant is in production or not. Thus, operation within the day is optimized based on variable costs, that is, fuel costs.

In addition, the flowchart of Fig. 8 assumes that the heat energy production and consumption are on average in balance. This means that the energy balance does not have to be corrected in any case. However, in reality, the energy balance may be disturbed, which results in a decrease in the water temperature in the district heating network if the CHP plant participates in the FCR. In this case, the energy balance could be corrected by energy trades in the intraday market.

6. Case example and calculation results

A case study was undertaken to demonstrate the operation of the proposed methodology. The study was implemented in the Simulink environment, which provides a good basis for a time sequence simulation. The simulation model is a techno-economic simulation where the elements of the CHP plant have been described as efficiencies of the process parts and power flows through the process. A basic description of the simulation process is presented in Fig. 9.

The case represents a small-scale CHP plant connected to a local district heating network. In the study, a 20 MW boiler, the maximum efficiency of which is assumed to be 85%, is modelled; thus, the maximum output power of the power plant is 17 MW. The maximum electricity production capacity is 6 MW. The minimum load of the boiler is 60% of the nominal power when the turbine is used. If electricity is not produced, the minimum load is 30%.

The suggested run mode for the power plant in normal operation is to run the turbine with 50% power, producing 3 MW electrical power if the heat demand allows the electricity production. In this operation, the power plant produces 14 MW heat. This allows the operator to participate flexibly in several energy markets, such as the electricity reserve markets, where the first option is to sell 50% of the electricity production capacity to the frequency reserve.

An example of the frequency reserve operation of a day is illustrated in Fig. 10, where the CHP operator has provided part of electricity production capacity to two reserve markets, FCR-N and FCR-D. For instance, both in the FCR-N and FCR-D markets, 2 MW of capacity is reserved for most of the day. It can be observed that only minor regulation actions are required. The activated frequency containment capacity is low compared with the reserved capacity. The sum of the maximum up-regulation capacity is 4 MW for most of the day, but the maximum up-regulation capacity in operation is approximately 2 MW. The activation of the reserve is based on actual frequency data of the day, presented in Fig. 1.

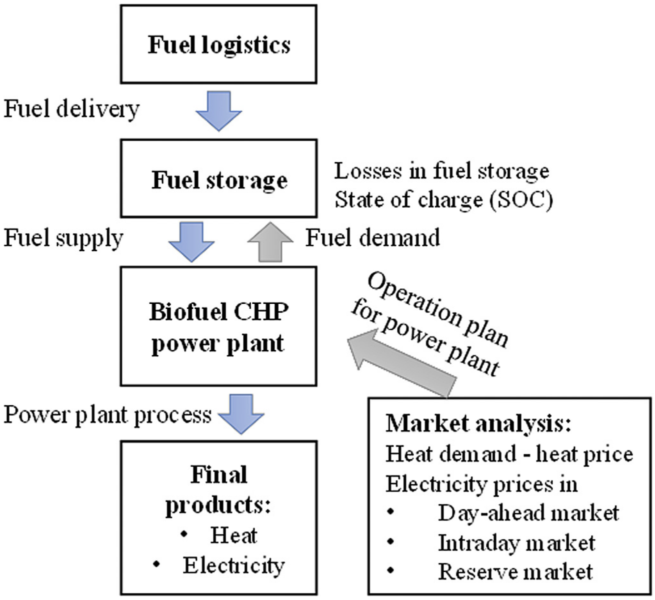

Fig. 9. Description of simulation model in the analysis.

The effect of FCR operation on the total electricity and heat production on the example day is illustrated in Fig. 11. It can be observed that the heat demand, and thus the production, is 15 MW for the day. Further, there is 2 MW of electricity production capacity available, which is sold to the electricity day-ahead market. This explains the 2 MW of capacity in the FCR-N market. However, because the maximum electricity production capacity is 6 MW, the remaining 2 MW production capacity is offered to the FCR-D market. Electricity up-regulation decreases the heat production, and vice versa. The average of the produced and delivered heat energy is 14.99 MW, in other words, there is a shortage of 0.34 MWh in the heat energy delivery, which accounts for 0.1% of the daily heat demand. This should not pose a problem, at least on this particular day.

The proposed methodology has been used to estimate the profits of large-scale exploitation of different market opportunities. To obtain an estimation of the increased business potential, we have carried out a scenario for traditional operation, where the reserve markets are not taken into account. Table 4 presents a feasibility comparison of two operation models of a CHP power plant: first, operation with reserve market participation and second, operation without reserve market operation. The costs and revenues of the second operation model are calculated with the same model as the first operation model. In this case, the reserve market offers are not included in the analysis.

As input, the comparison takes data from four markets: heat market, electricity day-ahead market, intraday market, and frequency containment reserve market, which provides the products FCR-N and FCR-D. The comparison is based on the data of years 2013–2015. The calculation is based on an estimated heat demand curve, where the peak demand occurs in wintertime, and in summer, the CHP power plant is closed for maintenance.

The analysis based on market data shows that participation in the reserve market increases the profitability of operation by 16–28% a year. This indicates that the new methodology significantly improves the profitability of the CHP plant operation. From the perspective of risk management the improved profitability enables for instance investments on process automation and enhanced power plant maintenance.

7. Discussion

The proposed methodology gives us an option to estimate the profitability of reserve markets for the CHP operator. To analyze the feasibility of the reserve market operation, we need an estimation of operation without reserves. This can be achieved with a similar model as for reserve market operation.

For a CHP power plant, a precondition for participation in the reserve markets is an opportunity to adjust the electrical power with a ramp to provide full power regulation at least in a few minutes. This is often possible by adjusting the reduction valve. There are also other alternatives such as adjusting the electric output power by using a heat pump, high-power resistors, or an electrical energy storage, but these are not considered in this study. The

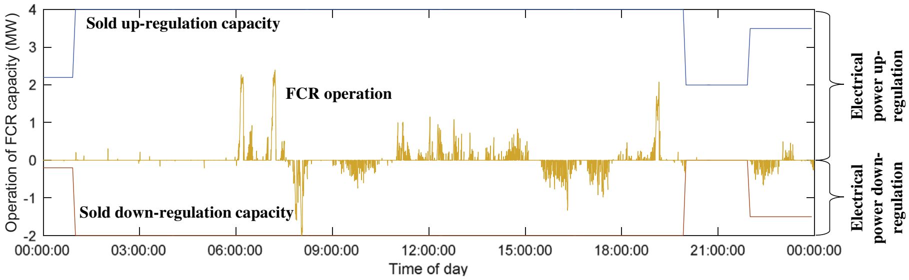

Fig. 10. Up- and down-regulation capacities and FCR operation when participating in the FCR-N and FCR-D markets in the example day 4 Feb. 2013.

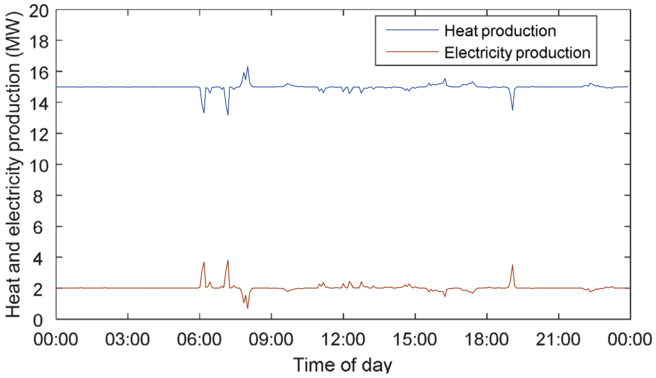

Fig. 11. Heat and electricity production when participating in the FCR-N and FCR-D markets on the example day, 4 Feb. 2013. The output powers are 5 min mean values.

opportunities of heat energy storages are not analyzed in depth, either.

However, even a market study shows that operation can be profitable, adjusting the electrical power may cause challenges to the heat delivery, because heat production is not constant, which poses a risk for the operation. In this case, the ability of the district heating network to store energy can be valuable, because it damps variation in production. The risk can be analyzed by considering the past frequency data. These data indicate that the risk is relatively small.

A challenge in the reserve market participation is that the volume of electricity reserve markets is limited. This means that new market participants may have a considerable effect on the reserve markets, which decreases reserve prices. For instance, in Finland, the electrical power capacity of district heating CHP is 4000 MW. If even a small proportion of the CHP capacity participates in the frequency containment reserve operation, the market will experience significant changes. For a comparison, the commitment of Finland to maintain the FCR-N is 140 MW and 220–265 MW for the FCR-D.

8. Conclusion

This paper presented a methodology to analyze a CHP operator's profit by participating in various heat and electricity markets, including both the present energy-based markets and capacity-based markets. The markets considered in the study are heat market, electricity day-ahead market, electricity intraday market, and electricity frequency containment reserve market. The markets are energy markets, except the electricity reserve market, which is a capacity-based market. A precondition for participation in the reserve market is that the high standards of reserve power containment have to be met. Typically, CHP power plants can meet the criteria by controlling the power output by adjusting the power-to-heat ratio by using a reduction valve. Naturally, this reduces the electrical energy production and thereby the sales. Nevertheless, the studies show that, at present, it is worthwhile to participate in the reserve market, yet at the expense of the day-ahead markets.

Reserve market participation may cause fluctuations in the heat delivery, and even minor shortages in heat delivery may occur if the electrical power has to be up-regulated for a long time. However, the CHP operator has several alternatives to prepare for this, such as by supplying heat proactively into the district heating system or by storing heat energy in the energy storage, where it can be discharged when required. In addition, utilization of heat pumps and battery energy storages could be attractive for the CHP operator; these solutions provide opportunities to optimize the business and balance production as effectively as possible. Nevertheless, these options have not been considered in this study, but they will be addressed in future studies.

Table 4
Costs and incomes of CHP operation with the Finnish electricity market prices of years 2013–2015 in cases where a small CHP operator is participating and not participating in the electricity reserve markets.

	2013		2014		2015	
	Reserve market [1000 €]	Without reserve market [1000 €]	Reserve market [1000 €]	Without reserve market [1000 €]	Reserve market [1000 €]	Without reserve market [1000 €]
Revenue total	**4470**	**4195**	**4149**	**3984**	**3855**	**3764**
Heat	3230	3230	3230	3230	3230	3230
Day-ahead	595	764	362	464	271	351
Intraday	343	201	352	290	195	183
FCR-N	233	0	153	0	105	0
FCR-D	69	0	52	0	54	0
Costs	**3242**	**3238**	**3113**	**3134**	**2913**	**2953**
Fuel	3242	3238	3113	3134	2913	2953
Profit	**1228**	**957**	**1036**	**850**	**942**	**811**

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