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Operation of district heat network in electricity and balancing markets with the power-to-heat sector coupling

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ABSTRACT

The stochastic nature of renewable energy resources poses a challenge in terms of balancing supply and demand in the power grid, necessitating additional sources of flexibility and balancing services. District heating networks (DHNs) equipped with power-to-heat (P2H) technologies and thermal storage can provide balancing services to the grid. Participation of DHN in a combination of diverse marketplaces to optimize revenue has been understudied. This study proposes a daily routine for the operation of a DHN in multiple energy markets, covering the day-ahead and intraday electricity markets, and various balancing markets. The emphasis is on providing balancing services by the P2H units, while considering their technical constraints of operation. The economic viability of the proposed routine is examined. Results indicate an increase in the operation profits by 1.3–9.7% compared to the total electricity sales, 0.4–3.0% of total heat sales, and 0.3–2.0% net profit in the examined DHN between 2019 and 2021. Given the complexity and uncertainty of future market development, it is critical to be aware of the most influential aspects. Sensitivity analysis indicates that fluctuations in electricity spot prices, fuel prices, and technical constraints of units significantly affect the profit.

1. Introduction

To comply with the European Union's (EU) strict net-zero emission targets for 2050 [1], a profound transformation of the existing energy systems is imperative to accommodate more renewable energy sources (RES) [2]. One of the challenges to achieve this purpose is that the intermittent and non-dispatchable nature of RES like wind and solar power and their stochastic production characteristics result in fluctuations in power balance, the equilibrium between electricity production and consumption [3]. Hence, the electrical power system should have flexibility to cost-effectively respond to an unanticipated deficiency or surplus in power production [4]. Electricity markets are designed to ensure adequate flexibility to the power grid so that supply matches demand at all times [5]. In the short run, the transmission system operator (TSO) preserves the grid frequency through balancing markets, which are the final stage of power trading before delivery [6]. The balancing markets ensure that sufficient electric capacity (i.e., reserve capacity) is always available to supply the required energy flow to preserve the grid frequency [7]. This necessitates the identification of additional sources of reserve capacity.

Coupling the power and heating sectors is a promising technique for increasing flexibility while also unlocking the significant emission reduction potential of the heating sector, as renewable electricity can be used to power heating technology [8–15]. Additionally, this integration enables higher efficiency and the utilization of less expensive thermal energy storage (TES) than electric storage [16]. Power-to-heat (P2H) technologies such as heat pumps (HPs) and electric boilers (EBs), as well as combined heat and power (CHP) technologies that operate at the interface between the two sectors provide several benefits to the electrical power system, including increased flexibility and network support, for example, reserve provision [17–21], congestion management and voltage control [22]. Utilizing small-scale P2H flexibility requires capacity aggregation via virtual power plants to bid on electricity markets [23,24]. On the contrary, many district heating networks (DHNs) already have a large electrical capacity due to the CHP plants. Most notably, DHNs are natural aggregators of heat demand and can set operating modes that permit the incorporation of higher shares of renewable energy sources without jeopardizing heat consumers' comfort, utilizing centralized TES [25]. Considering the large-scale deployment of HPs (the electrification trend) and the shutting down of fossil-fuel-based CHP units in the larger Finnish DHNs [9], as well as

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Nomenclature

Indices

i	CHP/HOB units in the DHN
j	Electricity-based units (HP, EB)
t	Time resolution

Parameters

$BP^{up/down}$	Upward/downward balancing price (€/MWh)
c^{CO_2}	Emission cost (€/MWh)
$c^{electricity}$	Electricity cost (€/MWh)
c^{fuel}	Fuel cost (€/MWh)
$c^{fuel-\cos t}$	fuel consumption cost (€/MWh)
$c^{fuel-tax}$	Fuel tax (€/MWh)
$c^{O\&M(i/j)}$	Variable operation and maintenance cost (€/MWh)
$CP^{up/down}$	Realized capacity prices of up/down-regulation (€/MW)
$COP_{(t)}^{HP(i)}$	Actual COP of HP at time t
$C_{prequalified}$	Prequalified reserve volume (MW)
$f(t)$	Grid frequency (Hz)
$H(t)$	Hourly heat demand (GWh)
$P_{\min}$	Current minimum power of a reserve unit (MW)
$P_{\max}$	Current maximum power of a reserve unit (MW)
$P_{\max}^{FCR-N}$	Maximum available power of a reserve unit in the FCR-N market (MW)
$P_{\max}^{FCR-D}$	Maximum available power of a reserve unit in the FCR-D market (MW)

Variables

$C_{accepted(t)}{}^{up/down}$	Accepted up/down-regulation capacity of a reserve unit (MW)
$C_{aFRR,up-reg(t)}$	Maintained volume of a reserve unit in the aFRR up-regulation market (MW)
$C_{aFRR,down-reg(t)}$	Maintained volume of a reserve unit in the aFRR down-regulation market (MW)
$C_{FCR-D/FFR(t)}$	Maintained volume of a reserve unit in the FCR-D/FFR market (MW)
$E_{(t)}^{(j)}$	Electricity consumption of a unit (MWh)
$F_{(t)}^{(i)}$	Fuel consumption of a unit (MWh)
$P_{activated(t)}$	Activated capacity of a reserve unit (MW)
$P_{activated,up/down(t)}^{EB}$	Activated power of the EB in up/down-regulation (MW)
$P_{activated,up/down(t)}^{HP}$	Activated power of the HP in up/down-regulation (MW)
$P_{(t)}$	current power setting of a reserve unit (MW)
$Q_{(t)}^{i/j}$	Produced heat of a unit (MWh)
$Q_{(t)}^{CHP(i)}$	Produced heat by a CHP unit (MWh)
$Q'^{CHP(i)}_{(t)}$	Increased heat production of the backup CHP in up-regulation (MWh)
$Q''^{CHP(i)}_{(t)}$	decreased heat production of the backup CHP in down-regulation (MWh)
$Q_{(t)}^{EB(j)}$	Produced heat of an EB (MWh)
$Q_{(t)}^{HOB(i)}$	Produced heat of a heat-only boiler unit (MWh)
$Q_{(t)}^{HP(j)}$	Produced heat of a HP (MWh)
$Q_{(t)}^{loss}$	Heat loss in the network (MWh)
$Q_{(t)}^{storage-ch\arg e/disch\arg e}$	Charged/discharged heat from the storage (MWh)
$Q'^{storage-disch\arg e}_{(t)}$	Discharge of the storage in up-regulation (MWh)
$Q'^{storage-ch\arg e}_{(t)}$	charge of the storage in down-regulation (MWh)
$R_{balancing\ market(t)}$	Revenue gained from balancing markets (€)
$R_{capacity-fee(t)}{}^{up/down}$	Capacity fee in up/down-regulation (€)
$R_{\mathrm{day-ahead}(t)}$	Revenue gained from day-ahead market (€)
$R_{energy-fee(t)}{}^{up/down}$	Energy fee in up/down-regulation (€)
$R_{heat(t)}$	Revenue gained from heat sales (€)
$R_{Intraday(t)}$	Revenue gained from intraday market (€)

the technical difficulties of regulating output in CHP configurations with backpressure turbines [26], this study assumes the provision of ancillary services from large-scale DHN-connected P2H technologies such as HPs and EBs.

The participation of P2H units in the balancing markets, majorly focusing on flexibility forecasting, load shifting, bidding techniques, and control concepts, is investigated in the literature [27]. investigated the possibility of utilizing HPs in Austria's automatic and manual frequency restoration reserve (aFRR, mFRR) markets and the day-ahead electricity market. The contributed business model showed that operating during low electricity prices in the day-ahead market saves costs and giving services for balancing markets brings additional revenue. The parallel provision of flexibility by HPs and EBs using the day-ahead market prices was discussed in Refs. [22,28,29]. [28] analyzed how likely the development of hourly electricity prices will affect the incentive to increase the use of TES and electric boilers for flexibility and [29] modeled HPs providing ancillary services from the economic point of view in Denmark. The studies used day-ahead market prices for their models. Results in both studies pointed out that the varying capacity and efficiency of HPs and EBs, and electricity market prices affect the profitability of the system [30]. examined the participation of a cluster of HPs with a combined capacity of 13.86 MW in the German aFRR market. The study focused on both the technical and financial sides of an aggregator system. The most challenging factor was found the minimum running time for HPs, which was determined as 30 min, as short cycling cycles had a detrimental impact on the lifespan of HPs. A comprehensive literature review including the target markets and the size of reserve units in each study is given in Table A 1 in appendix A. However, some research issues have remained understudied.

As shown in Table A1, a limited number of marketplaces are examined in each study, and others are often neglected. A DHN operator can increase its profit by participating in a combination of available marketplaces, explained in the following sections. Furthermore, technical constraints of a reserve units, i.e., start-up and shut-down periods, ramp rate, and minimum running load, restrict the potential capacity that the unit can contribute to the balancing markets. This point is also overlooked in the literature [31]. The interaction between reserve units in a DHN and other production units that do not participate in the balancing markets is sometimes ignored in the literature [32]. This is important in the sense that the provision of balancing services from a reserve unit may disrupt the heat demand balance, which is the priority of a DHN operator. Considering the mentioned research gaps, this study examines the techno-economic feasibility and operation of a DHN in all conceivable liberalized energy markets, including the heat energy market, the day-ahead and intraday electricity markets, and various balancing markets considering the technical limitations of reserve units. As previously stated, P2H technologies (HPs and EBs) in the DHN provide balancing markets with reserve capacity. The contributions of this study can be categorized as follows:

- Conducting literature and industry reviews to ascertain the technological constraints on HPs and EBs participating in the balancing markets
- Proposing a daily operational routine for the DHN operator to maximize revenue by concurrently operating assets in multiple markets
- Conducting a sensitivity analysis to ascertain the most significant elements affecting revenue from balancing markets

2. Background: markets and technologies

The following section examines the various electricity and balancing markets in the EU, emphasizing the Nordic countries. As district heating is a natural monopoly in Finland, there is not a competitive market for heat, so heat prices are not regulated; however, competition authority controls the reasonability of prices and abuse of dominant position [33].

2.1. Electricity markets

In the Nordic countries, the electricity market consists of many marketplaces that serve as "time windows" for physical energy trading: the day-ahead and the intraday markets [34].

2.1.1. Day-ahead market (Elspot)

This is the part of the primary wholesale market through which buyers and sellers trade electricity for the following day (day D). All the participants bid the price and quantity they are willing to buy or sell energy for each hour. The market closes every day at 12:00 CET and the price for each hour is formed by the Merit Order principle [35]. Nordpool publishes results for the corresponding day around 2:00 p.m [36].

2.1.2. Intraday market (Elbas)

This market is continuous. It remains open 1 h prior to delivery after the closing time of the day-ahead market and a pilot of closing at the delivery time in the Finnish bidding zone has already been implemented [37]. This market balances the differences between supply and demand if unexpected changes occur in consumption or production. The price is based on the "pay-as-bid" principle [38]. The increasing amount of RES has affected both Elspot and Elbas markets. Renewables have almost zero marginal cost, which moves the Merit Order curve towards low prices. This means that hydro, wind, and nuclear dominate the market price by setting it low and decreasing the profits of energy production while the most expensive forms of energy, including conventional power plants, become unprofitable. The natural balancing properties of the electricity grids (inertia) decrease as the conventional power plants become less profitable and are shut down. Thus, more applications with fast balancing capabilities, like batteries, HPs and EBs, are needed [35].

2.2. Reserve markets

There should always be a balance between electricity supply and demand, indicated as the frequency of the system [3]. In the EU, frequency is allowed to fluctuate between 49.9 and 50.1 Hz [3]. Fig. 1 represents the system frequency in Finland on the 1st of January 2022 [39], indicating that frequency had to be regulated many times.

TSOs are responsible for procuring required reserve capacity via the balancing markets [3]. In Finland, these markets consist of frequency containment reserve for normal operation (FCR-N), frequency containment reserve for disturbances (FCR-D), fast frequency reserve (FFR), and frequency restoration reserves, activated automatically (aFRR) or manually (mFRR). In Table 1, the key characteristics and requirements of each of the products, as of year 2021, specified by local Finnish TSO, Fingrid [3], are summarized. For each hour, Fingrid places the bids in the price order, with the principle of giving priority to the cheapest bid. A necessary volume of the bids is used in the price order, separately for upward balancing and downward balancing capacity. The opening and closing hours of various marketplaces in Finland are depicted in Fig. 2 [3].

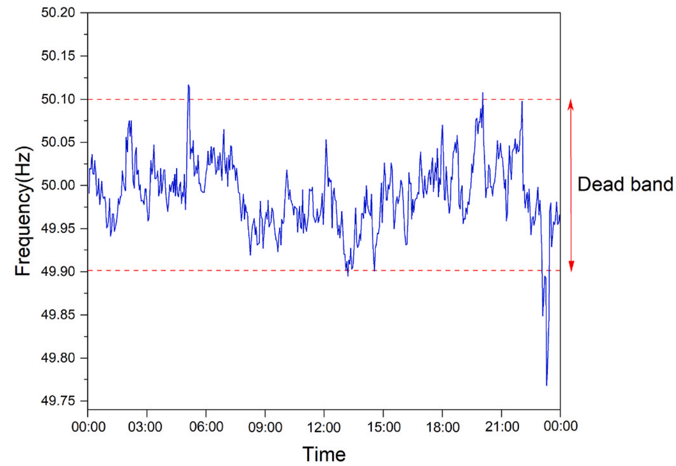

Fig. 1. Frequency variation in Finland, 1st of January 2022 [39].

2.3. Technical challenges of reserve units in providing balancing services

To identify the best marketplaces for the studied reserve units (HP and EB in this study), this subsection investigates their technical constraints in different balancing markets via industry and literature reviews. There is limited knowledge of the time scale that large HPs can adapt their load and the dynamic effects during fast regulation [40,41]. The ramping time can be constrained by factors such as mechanical wear of the components, start-up time of several minutes, and low COP during start-up [40–42]. investigated the possibility of large-scale ammonia HPs to supply ancillary services to the power grid and the limitations of fast ramping up and down of the HPs [40]. sought to quantify the dynamic behavior and limitations of two-stage ammonia HP cycles concerning fast ramping. According to the study, the HP should run on partial load up to full load rather than being shut down entirely and restarted. The reason for doing this procedure is that necessary settling and compressor waiting times can be then avoided. Conclusions from Ref. [42] state that operating in a partial load-condition or forecast-based scheduling is required for HPs to be able to provide balancing services. In other words, HP ramping is significantly faster if the systems remain pre-heated or in a partial load [41]. analyzed the dynamic behavior of two HP configurations, a one-stage and a two-stage ammonia HP, during a load change. The results showed that the limiting factor is the thermodynamic effect, i.e., the walls of the suction line warm up slower than the fluid warms up due to the thermal inertia of the material used in the piping. Thus, the temperature of the wall was below the saturation temperature of the fluid, which would lead to condensation along the pipe walls. In addition, this effect was more substantial the faster the ramping down was. This would harm the compressors. To point out, there is no problem when ramping up, as the suction line is warmer than the saturation temperature.

In conclusion, research findings emphasized that the dynamic behavior of HPs is strongly affected by the controller design, so providing secondary regulation power (a response time below 5 min required for FCR and FFR markets) should not be considered unless improvements are made to the design of HPs. Three major importer companies in Finland were also interviewed [43–45]. Findings indicate that the required activation time for the FCR-N market (3 min) cannot be achieved with MW-size HPs. The reasoning behind this was that otherwise, the compressor would be exposed to significant mechanical stress and it could break down. However, according to product manuals and discussion with HPs producers, small-scale HPs in the kW range are allowed to have a minimum pause/waiting time of 3 min. EBs, on the

Table 1
Different reserve products and their requirements in Finland [3].

Product	FCR		aFRR	mFRR	FFR
	FCR-N	FCR-D			
Purpose	Maintaining the frequency in the standard range (49.9–50.1 Hz)	In big frequency deviations	To return the frequency to its normal range	Activated if necessary	In big frequency deviations in low inertia situations
Procurement channel	Yearly/hourly markets Other Nordics/Estonia Vyborg DC link	Yearly/hourly other Nordics	Hourly market Sweden	Fingrid's reserve power plants	hourly market Estonia
Typically needed	All the time	In larger frequency deviations	Partial hours of day	When necessary	Spring, summer, and autumn (especially weekends and nighttime)
Payment	Capacity payment Activation payment	Capacity payment	Capacity payment Activation payment	Capacity payment Activation payment	Capacity payment
Bid submission	18:00 yearly 18:30 hourly	18:00 yearly 18:30 hourly	17:00 yearly	45 min before delivery	18:00 yearly 18:30 hourly
Bid information	product (FCR-N or FCR-D) capacity (MW) price of availability (€/MW,h) hour (EET time zone).		Product (aFRR) Capacity (MW) up Capacity (MW) down Price of capacity, up (€/MW,h) Price of capacity, down (€/MW,h) Hour (EET time zone)	–	FFR bid or a combination bid capacity (MW) price of availability (€/MW,h) hour (EET time zone)
Bids	Symmetrical	asymmetrical	asymmetrical	asymmetrical	asymmetrical
Max/Min bid (MW)	5/0.1	10/1	N/A/1	N/A/10	10/1
Bid accuracy (MW)	0.1	0.1	1	1	0.1
Activation method	Linearly based on frequency deviation	Linearly based on frequency deviation	Activates continually according to an activation signal sent by Fingrid within 5 min.	Activates manually upon Fingrid request	Automatic
Response (Activation speed)	Full activation in max 3 min	50% in 5 s, 100% in 30s	Full activation in max 5 min	Full activation in max 15 min	Full activation in max 1.3 s
Duration	At least 30 min per direction	At least 30 min per direction	1 h	1 h	Min 5 s–20 s (depend on the deactivation speed)

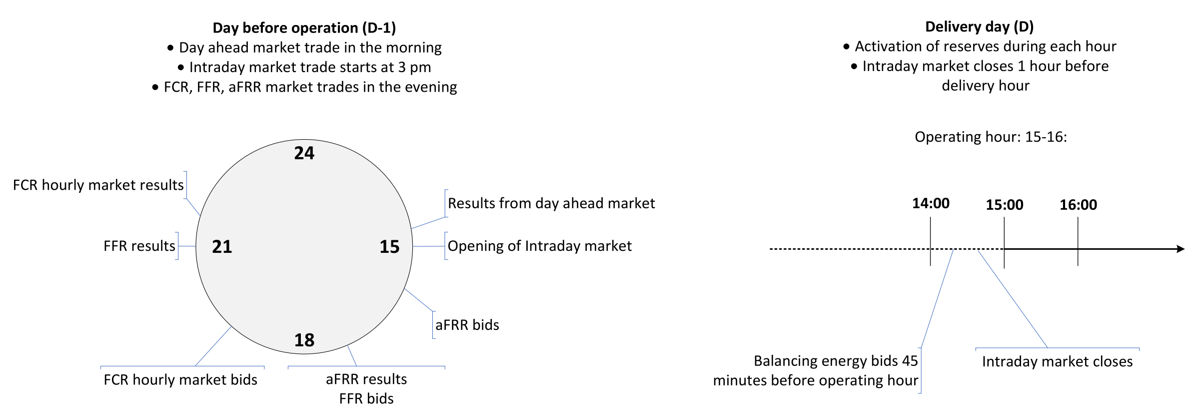

Fig. 2. Timetable of electricity and reserve markets [3].

other hand, do not have ramping restrictions. They can ramp up and down rapidly, offering greater flexibility than HPs [46].

3. Methodology

This section outlines the methodology behind the proposed daily operation routine for DHN operators to participate in different electricity (day-ahead and intraday) and balancing markets. First, a typical electrified DHN, including power-to-heat units (HP, EB, and CHP), peak boilers, and TES, is optimized to meet heat demand with the lowest heat production cost. Next, an hourly operational routine for the DHN operator is proposed based on the opening and closing times of electricity and balancing markets. It is intended to maximize the revenue for the operator by allocating the maximum capacity of reserve-providing units (HP and EB in this study) at each time resolution (1 h in this study) to different markets. A description of the daily operation routine is provided in Section 3.1. Section 3.2 presents the mathematical model and equations for energy and economic analyses. A hypothetical DHN, including a real Finnish city DHN, integrated with HP and EB in the simulations is examined as a case study in section 3.3 to evaluate the viability of the proposed operation routine.

The case study is simulated for the period 2019–2021. In 2019, electricity prices were regular, averaging 44 €/MWh [39], whereas, in 2020, prices declined significantly (average of 28.0 €/MWh [39]). During 2021, the average price reached a record level of 72 €/MWh [39]. Thus, this period of different electricity prices could provide a better insight into the results and operation of the DHN in different markets based on the proposed operation routine. Simulations are performed using historical inputs, including day-ahead electricity prices, fuel prices, EU ETS prices, weather data, balancing capacity prices, and real-time frequency for 2019–2021. The following assumptions are considered in this analysis:

- The priority of the DHN is to provide an uninterrupted heat supply for all customers.
- It is assumed that only HP and EB participate in the balancing markets in a parallel manner.
- Electricity generated by the CHP units is exchanged in the day-ahead and intraday electricity markets with the realized prices, while in reality, companies also hedge their electricity sales.
- HPs exclusively participate in the aFRR balancing market, which requires a longer activation time (5 min), while EBs can participate in all available balancing markets (FCR, FFR, and aFRR).
- CHP (with a fixed heat to electricity ratio) and TES in the DHN can compensate for the imbalanced heat generation caused by the up/down-regulation of HP and EB.
- This study has excluded participation in the mFRR market due to decreasing demand for this market in Finland and larger minimum bid requirements.

Fig. 3 illustrates the schematic of the studied DHN and various marketplaces.

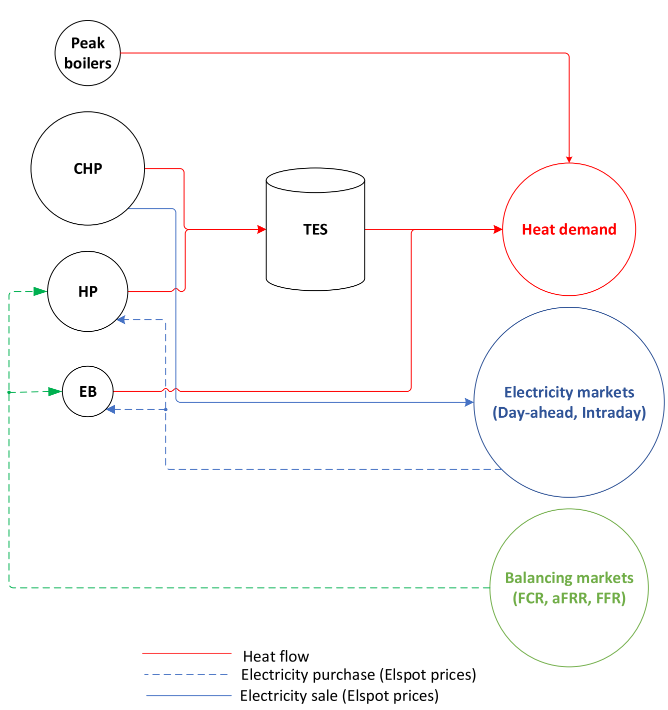

Fig. 3. A schematic of the studied DHN and different markets.

3.1. Operation of the DHN

Fig. 4 illustrates the main steps of the examined DHN in various marketplaces according to the proposed routine.

The first objective is to determine the optimal operation of the DHN while producing the required heat demand. EnergyPro software is used to simulate the optimal operation of the DHN while producing heat [47]. The optimization routine is to minimize the heat production cost based on the marginal production costs of the units on hourly basis (step 1 in Fig. 4). Electricity generated by CHP units is then traded on the first open electricity market, day-ahead (step 2). Subsequently, the operator separately offers the available capacity of HP and EB to the balancing markets in the order of their operating hours, as shown in Fig. 2. Following aFRR market (step 3), FFR and FCR-D are the next marketplaces in which a combined bid can be offered [3] (step 4). For combination bids (FFR + FCR-D hourly market), FFR is traded first. If the combination bid is used on the FFR market, the bid will not be transferred to the FCR-D market; otherwise, the bid is offered to the FCR-D market. Due to the previous justifications, only the EB can participate in the FCR and FFR markets.

The goal in the balancing markets is to maximize profit by allocating the maximum amount of capacity to each market at each time step (1 h in this study). While there are positive imbalances (demand exceeds supply), reserve units provide downward reserve (down-regulation) by increasing electricity consumption when not operating at full capacity. While in the event of negative imbalances, in which demand exceeds supply, reserve units provide upward reserve (up-regulation) by reducing electricity consumption while not operating at minimum load. If the reserve unit is running near its full capacity in the determined operation routine in step 1 ($P_{max} - P_t < P_t - P_{min}$), capacity should be allocated for up-regulation; however, if the reserve unit is operating near the minimum load ($P_{max} - P_t > P_t - P_{min}$), it is more economically advantageous to offer a down-regulation bid to the market. The mathematical equations are presented in the following subsection.

Following the activation of reserve units during the operation day (it is possible that only a fraction of the offered capacity to a market would get activated in the operation day), heat imbalances would be compensated for by the backup CHP and TES (steps 5 and 6). Down-regulation would result in excess heat production by reserve units (HP and EB in this study), which would not be a concern in satisfying heat demand. Hence, the backup CHP can reduce its production level if it is not operating at the minimum load, or TES can be charged (step 7). This decision requires a trade-off between cost savings gained from reduced fuel consumption in the backup CHP and income loss from the electricity sales when the CHP decreases its production level. If decreasing CHP output is more profitable (fuel savings > lost electricity sales from the CHP), the operator should compensate for the decreased CHP electricity production previously sold to the day-ahead market by purchasing that amount from the intraday market (step 8). Up-regulation leads to a decrease in the heat generated by HP/EB. To satisfy the heat demand, the operator opts between increasing the CHP output, if not running in its maximum load, and discharging TES. The increased CHP electricity production can be sold to the intraday market (step 8). Fig. 5 depicts the daily routine of the DHN operator according to the proposed routine. The operation of the DHN in the balancing markets is simulated in MATLAB, which provides a reasonable basis for evaluating time sequences [48].

3.2. Mathematical modeling

3.2.1. Energy analysis

Eq. (1) minimizes the heat production costs of the DHN based on the marginal production costs of units, i.e., fuel costs (c^{fuel}), variable operation and maintenance costs ($c^{O\&M}$), and the electricity costs ($c^{electricity}$) of HP/EB. Fuel cost is comprised of fuel consumption cost ($c^{fuel-\cos t}$), emission cost of fuel (c^{CO_2}) and fuel tax ($c^{fuel-tax}$). Heat demand balance is indicated by Eq. (3). i signifies the CHP/HOB units, whereas j denotes HP/EB units.

$$\min\left[\sum_{i,j=1}^{n}\sum_{t=1}^{8760} F_{(t)}^{(i)} c^{fuel(i)} + E_{(t)}^{(j)} c_{(t)}^{electricity(j)} + c^{O\&M(i/j)} Q_{(t)}^{i/j}\right] \tag{1}$$

$$c^{fuel(i)} = c^{fuel-\cos t(i)} + c^{CO_2(i)} + c^{fuel-tax(i)} \tag{2}$$

$$Q_{(t)}^{CHP(i)} + Q_{(t)}^{HOB(i)} + Q_{(t)}^{HP(j)} + Q_{(t)}^{EB(j)} + Q_{(t)}^{storage-disch\arg e} - Q_{(t)}^{storage-ch\arg e} - Q_{(t)}^{loss} = H_{(t)} \tag{3}$$

The maintained volume for a reserve unit that consumes electricity

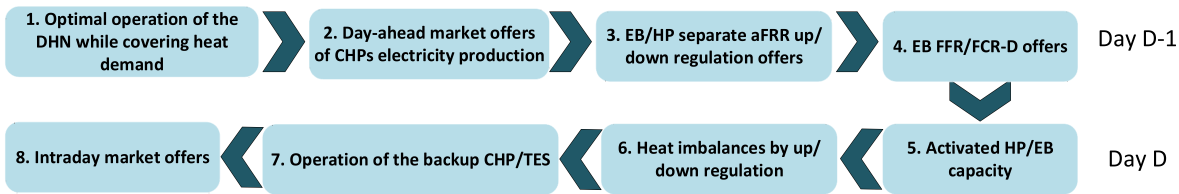

Fig. 4. Main steps of the operation of the DHN in different markets.

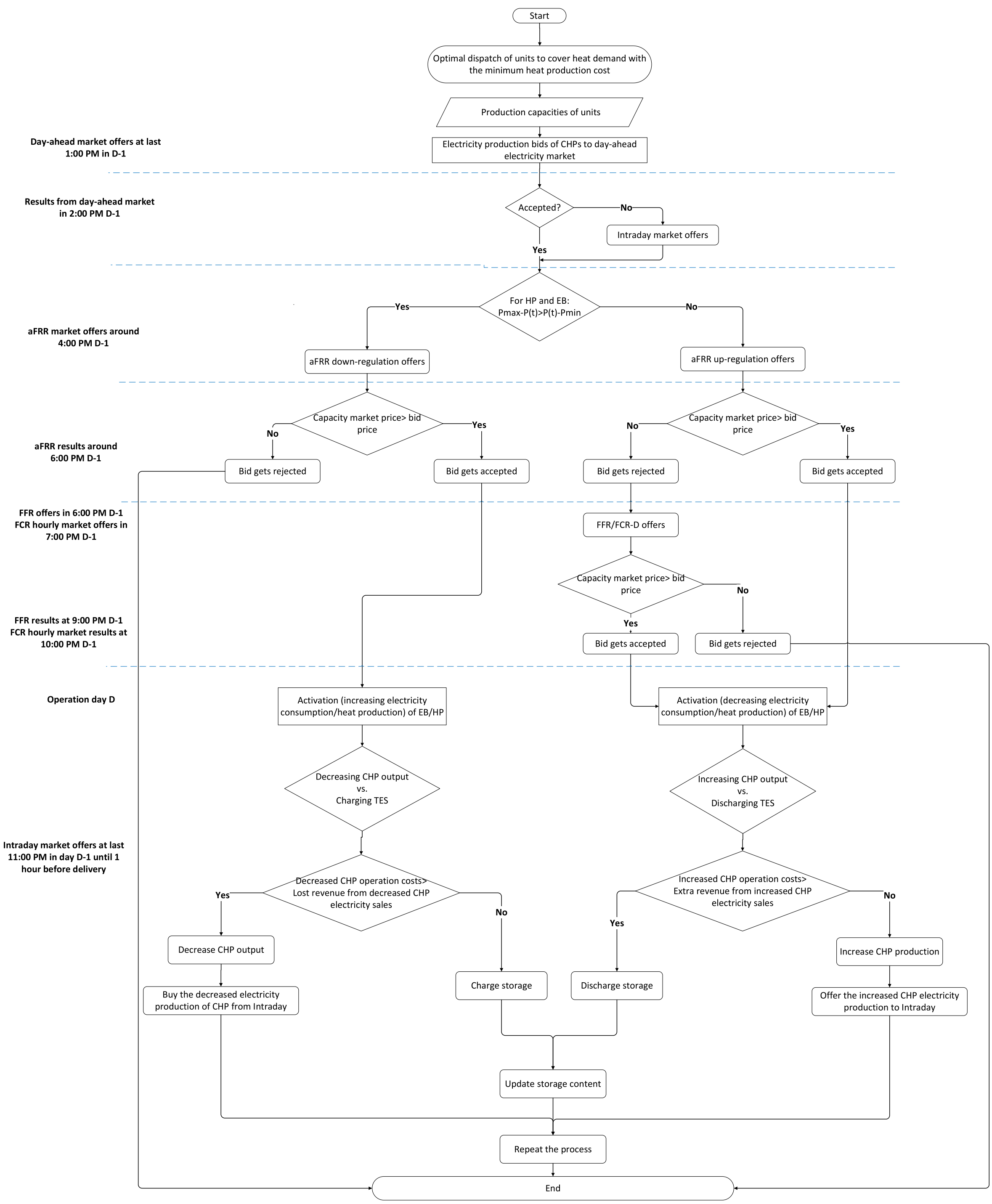

Fig. 5. The flowchart of the operation of the DHN in different electricity and balancing markets. t refers to the hours of the operation day.

in the studied balancing markets can be calculated using Eqs. (4)–(6) [3]. The maximum and minimum power of the reserve unit are denoted with $P_{\max}$ and $P_{\min}$, respectively. $P_{(t)}$ Is the current power setting of the reserve unit, i.e., the power of the reserve unit excluding any activated power and $C_{prequalified}$ indicates the reserve volume verified by prequalification tests conducted by the TSO. It is presumed that all the capacity that a reserve unit can offer is prequalified by the TSO beforehand.

$$C_{aFRR,up-reg(t)}=\max\left[\min\left(P_{(t)}-P_{\min},C_{prequalified}\right),0\right] \tag{4}$$

$$C_{aFRR,down-reg(t)}=\max\left[\min\left(P_{\max}-P_{(t)},C_{prequalified}\right),0\right] \tag{5}$$

$$C_{FCR-D/FFR(t)}=\min\left(P_{(t)}-C_{aFRR},C_{prequalified}\right) \tag{6}$$

In the FCR markets, the capacity of a reserve unit is activated linearly based on the local measured frequency, as illustrated in Fig. 6 [3]. Linear activation guarantees equal activation for all service providers. The negative sign implies down-regulation, while the positive means up-regulation. The linear activation is mathematically expressed in Eq. (7). $f_{(t)}$ denotes the measured local frequency, while $P_{\max}^{FCR-N}$ and $P_{\max}^{FCR-D}$ refer to the maximum available power of a reserve unit in FCR-N and FCR-D markets. The activation of aFRR is based on a power change signal calculated based on the frequency deviation in the Nordic synchronized area and is sent by the TSO [3].

Eq. (8) expresses the hourly heat demand balance following the activation of the reserve units. $Q'^{CHP(i)}_{(t)}$ and $Q''^{CHP(i)}_{(t)}$ indicate the increase or decrease in heat production from the backup CHP to compensate for the heat imbalances caused by the activation of reserve units (step 7 in Fig. 4). Likewise, $Q'^{storage-charge}_{(t)}$ and $Q'^{storage-discharge}_{(t)}$ represent the amount of charged or discharged heat from the TES after the activation of reserve units on the operation day. $P_{activated,up/down(t)}$ represents the activated capacity of a reserve unit in up/down-regulation separately.

$$\left(Q_{(t)}^{CHP(i)}+Q_{(t)}^{HOB(i)}+Q_{(t)}^{HP(i)}+Q_{(t)}^{EB(i)}+Q_{(t)}^{storage-discharge}-Q_{(t)}^{storage-charge}-Q_{(t)}^{loss}\right)+ COP_{(t)}^{HP(i)}\left(P^{HP}_{activated,down(t)}-P^{HP}_{activated,up(t)}\right)+\eta^{EB(i)}\left(P^{EB}_{activated,down(t)}-P^{EB}_{activated,up(t)}\right)+ \left(Q'^{CHP(i)}_{(t)}+\eta_{dis}{}^{TES}Q'^{discharge-TES}_{(t)}\right)-\left(Q''^{CHP}_{(t)}+\eta_{dis}{}^{TES}Q'^{charge-TES}_{(t)}\right)=H(t) \tag{8}$$

3.2.2. Economic analysis

Acceptance criteria for bids submitted to each balancing market are as follows: if the operator can submit a bid with less price than the market-accepted capacity price for that hour, the bid is accepted. While providing up-regulation, the minimum bid price should cover the costs of producing diminished heat supply in up-regulation by the backup CHP (fuel and O&M costs). The minimum bid price for down-regulation is calculated as the cost of increasing the electricity consumption of HP/EB.

Balancing service provider receives compensations for providing balancing services. The capacity fee is the compensation paid by a TSO to a balancing service provider for maintaining a reserve for an accepted bid. It is important to note that only a part of an accepted capacity in a particular hour may get activated on the operation day. Energy Fee refers to the compensation paid for the activation of the reserve. In an over-frequency situation, the TSO charges from the balancing service provider an energy fee for the balancing energy sold by the TOS to the balancing service provider. In an under-frequency situation, the TSO pays an energy fee that corresponds to the purchased balancing energy to the balancing service provider. The capacity and energy fees and the revenue from balancing markets are expressed via Eqs. (9)-(11) [3].

$$R_{capacity-fee(t)}{}^{up/down}=C_{accepted}{}^{up/down}.CP^{up/down} \tag{9}$$

$$R_{energy-fee(t)}{}^{up/down}=\left(P_{activated,up/down(t)}*T^{i}_{(t)}\right).BP^{up/down} \tag{10}$$

$$R_{balancing\ market(t)}=R_{capacity-fee(t)}{}^{up/down}+R_{energy-fee(t)}{}^{up/down} \tag{11}$$

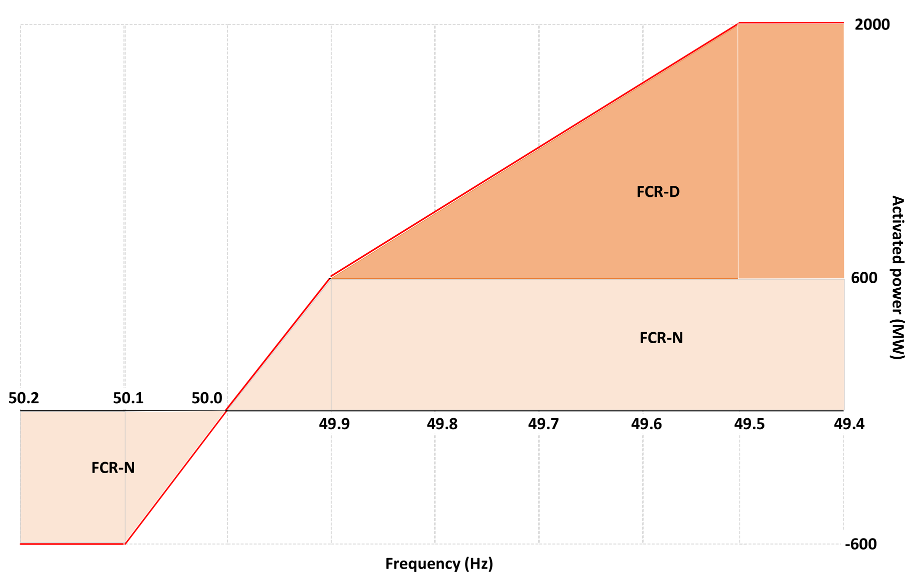

Fig. 6. Activation of a reserve unit as a function of frequency in the FCR markets [3].

$$P_{activated(t)}=\left\{\begin{array}{l}-P_{\max}^{FCR-N}\ ;\ 50.1<f(t)<50.2\\ +P_{\max}^{FCR-N}(-10f(t)+500)\ ;\ 49.9<f(t)<50.1\\ +P_{\max}^{FCR-N}+P_{\max}^{FCR-D}(-2.5f(t)+124.7)\ ;\ 49.5<f(t)<49.9\\ +P_{\max}^{FCR-N}+P_{\max}^{FCR-D};\ 49.4<f(t)<49.5\end{array}\right\} \tag{7}$$

The capacity fee is determined by the product of the accepted capacity in the auction ($C_{accepted(t)}{}^{up/down}$) and the realized capacity price of the corresponding hour ($CP^{up/down}$). The energy fee is obtained by multiplying the activated energy in the corresponding balancing market ($P_{activated.up/down(t)} * T^{i}_{(t)}$) by the upward/downward balancing price ($BP^{up/down}$). The up-regulation price is the price of the most expensive mFRR up-regulation bid ordered; however, at least the price for the bidding area of Finland in the day-ahead market during the hour in question. The down-regulation price is the price of the cheapest mFRR down-regulation bid ordered; however, no more than the price for the bidding area of Finland in the day-ahead market during the hour in question [3]. The DHN operator's total revenue from all markets is indicated by Eq. (12).

$$Total\ revenue = \sum_{t=1}^{8760}\left[R_{heat(t)} + R_{\text{day-ahead}(t)} + R_{Intraday(t)} + R_{balancing\ market(t)}\right] \tag{12}$$

3.3. Case study

To validate the feasibility of the proposed operation routine, we simulate a hypothetical medium-sized Finnish city. This is based on a real city network, but the electrified technologies are hypothetical. The system includes a TES, a waste-water HP (WWHP), and an EB. Fig. 7 depicts the schematic of the studied DHN and all units with their technical properties. Due to the shorter maintenance period than CHP1 and the year-round availability of biomass, CHP2-biomass is considered the backup CHP [9]. contains a comprehensive discussion of the parameters and input data.

Table 2 summarizes the input data and simulation procedure of this study.

Table 2
Modeling process of the case study DHN.

	Inputs	Process	Outputs
First stage	- Hourly outdoor temperature [49] - Electricity spot prices [36] - Fuel costs (fuel, CO_2, carbon prices) [50] - O&M of units [51] - HP input/output hourly temperatures [52] - Electricity tax and distribution costs [53] - Heat demand [53] - Storage capacity [53]	- Simulation of the case study DHN - Objective: minimizing heat production costs based on marginal production costs of units - Markets:	- Optimal operation of the DHN - Hourly production/ consumption of units - Hourly storage content
Second stage	- Hourly optimal operation of the units from the first stage - Realized day-ahead prices [3] - Realized Intraday prices [38] - Realized capacity prices in different balancing markets [3] - Up/down-regulation prices [3] - Measured local frequency [3]	- Objective: Maximizing total revenue from electricity and balancing markets - Markets: Day-ahead, Intraday, aFRR, FCR-D, FFR - Sensitivity analysis of different parameters	- Revenue from different markets - The effects of different parameters on the DHN operation

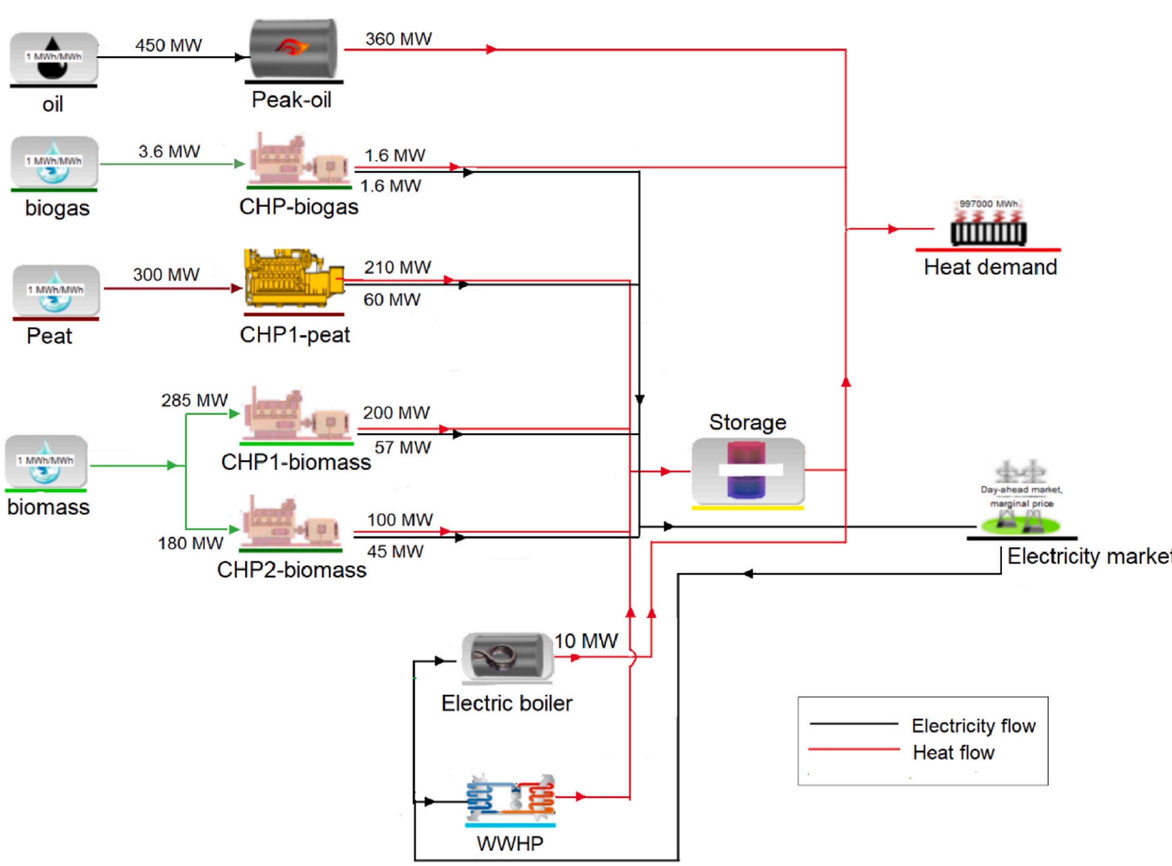

Fig. 7. The schematic of the studied DHN.

4. Results and sensitivity analysis

This section summarizes the findings from the simulation of the studied DHN, considering the participation of EB and HP units in various balancing markets between 2019 and 2021. Table 3 presents the breakdown of the economic results derived from the proposed operational routine for the case study DHN. Due to the implementation of the FFR marketplace in Finland in late 2020 and the lack of data [3], it is not considered in this analysis. Revenue from electricity markets is calculated as the electricity sales of all CHP units in the studied DHN. Negative signs for the intraday electricity market indicate that electricity is being purchased.

According to Table 3, participation in the balancing markets using the suggested operation routine results in economic benefits without additional investments. In 2019–2021, this revenue accounted for 0.4–3.0% of yearly heat sales and 1.3–9.7% of total electricity sales of the DHN. This additional revenue is significant because the competition authority regulates DHN pricing in Finland. This means that operators can earn a limited marginal profit on DH sales. On the contrary, electricity and balancing markets are competitive, generating additional economic revenue streams.

To justify the results in Table 3, Fig. 8 compares revenue from various marketplaces to annual average electricity prices and the average up/down-regulation prices in the Finnish area [39]. The higher revenue from electricity markets in 2021 compared to the previous years is explained by record-high spot prices in 2021. On the other hand, low electricity prices in 2020 resulted in a significant decline in electricity sales revenue (56% lower revenue compared to 2021). However, using the proposed operation routine, the operator can benefit from the additional revenue from the balancing markets, avoiding economic losses in years with lower electricity prices, like 2020. Notably, in years with higher electricity prices, offering up-regulation is more profitable due to the savings realized from decreasing the high-cost electricity consumption of HP and EB. However, in 2020, with lower electricity spot prices, offering down-regulation becomes more economical, as cheaper electricity is available to increase the production of HP/EB (providing down-regulation) and hence deliver heat at a lower cost than without participation in the balancing markets.

Electricity market revenue is directly related to electricity spot prices, whereas balancing market revenue is also affected by other parameters. Given the complexity and uncertainty surrounding future market development, it is critical to identify the primary factors affecting the operation of DHN in these markets.

The findings of the sensitivity analysis conducted for 2021 suggest that revenue is impacted by variations in several parameters, including electricity spot prices, fuel prices, and technical constraints of units. 2019 and 2020 produced comparable results. The effects of day-ahead and up/down-regulation prices are depicted in Fig. 9. The graph also supports the preceding discussion following Table 3 that up-regulation generates more revenue during high electricity prices. In contrast, in lower electricity prices, down-regulation is more economically beneficial.

The ramp rate is a physical property of each power plant that describes the rate at which output increases or decreases per minute in spinning mode. It is typically expressed in %/minute or MW/min [54]. Apart from the capability of HP/EB for fast ramping required for the balancing markets, the ramp rate of the backup CHP also affects the capacity of HP and EB that can be offered to the balancing markets. Ramp rate is determined by the capacity of the producing unit, the operating conditions (whether the unit is starting up or operating at a minimum load hold point), and optional technologies for reducing startup time and improving ramp rate. The ramp rate of a power plant is also dependent on the number of units and their configuration. Fig. 10 demonstrates that increasing the ramp rate above 5% increases the achievable revenue rapidly until it reaches a plateau at a ramp rate of 35%. The power plant in this case is able to ramp significantly within 15 min compared to the size of the HP. Thus, the forthcoming change to 15-min market resolution may bring further opportunities.

Fuel cost of the backup CHP (biomass price) also contributes significantly to revenue from balancing markets, as illustrated in Fig. 11. The CHP should compensate for heat deficiency while providing up-regulation. This explains the downward trend in revenue from up-regulation depicted in Fig. 11. On the other hand, for down-regulation services, a higher fuel price results in more significant savings from reduced CHP operation.

According to Fig. 12, the optimum electrical capacity of HP for the studied DHN is 25–30 MW. While revenue from down-regulation increases as the capacity of HP increases (because the HP can consume electricity at a lower price than the day-ahead price when providing down-regulation), revenue from up-regulation decreases after the optimal capacity. This is because the backup CHP's fuel and O&M costs increase as it compensates for the significant amount of heat lost due to the HP up-regulation. For the EB, revenue increases steadily as the capacity of the EB increases, as illustrated in Fig. 13. In this case up-regulation bid was accepted 1866 h of the year and down-regulation was accepted 2292 h, yet up-regulation generated significantly more income.

5. Conclusion

The purpose of this study is to conduct a techno-economic analysis and evaluate the economic feasibility of participation of a district heat network (DHN), including power-to-heat (P2H) units such as combined heat and power (CHP) units, heat pumps (HPs), electric boilers (EBs), and thermal energy storage in different liberalized markets, i.e., heat, electricity, and balancing markets in Finland. The emphasis is on the provision of balancing services by HP and EB. The participation of reserve units in various balancing markets, considering their technical constraints and requirements of each market is also investigated. An

Table 3
Modeling results of the case study DHN with the proposed operational routine (all results are in million euros).

	2019		2020		2021	
	No reserve market	Reserve market	No reserve market	Reserve market	No reserve market	Reserve market
Revenue from heat sales	57.2	57.2	55.6	55.6	55.6	55.6
Revenue from day-ahead electricity sales	14.8	14.8	11.6	11.6	26.4	26.4
Revenue from Intraday electricity sales	0.0	−0.01	0.0	−0.05	0.0	−0.01
Total revenue from electricity markets	14.8	14.8	11.6	11.5	26.4	26.4
Revenue from up-regulation	0.0	0.2	0.0	0.8	0.0	1.4
Revenue from down-regulation	0.0	0.4	0.0	1.0	0.0	1.2
Total revenue from balancing markets	0.0	0.6	0.0	1.8	0.0	2.6
Total revenue	72.0	72.6	67.2	68.9	82.0	84.6
Costs (O&M, electricity, fuel)	39.3	39.7	34.7	35.3	45.3	46.2
Profit	32.7	32.9	32.5	33.6	36.7	38.4
Net income from balancing market participation	0.2		1.1		1.6	

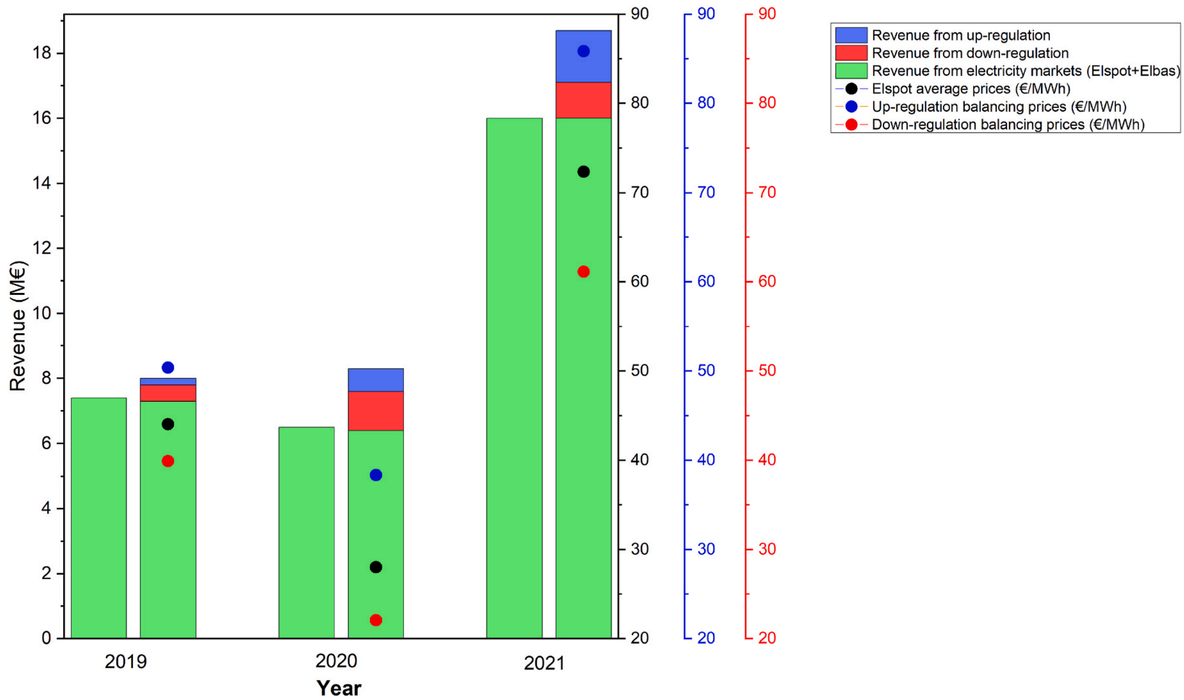

Fig. 8. Comparing incomes from electricity and balancing markets with average spot and up/down-regulation prices. (Income from electricity markets is depicted just for the backup CHP).

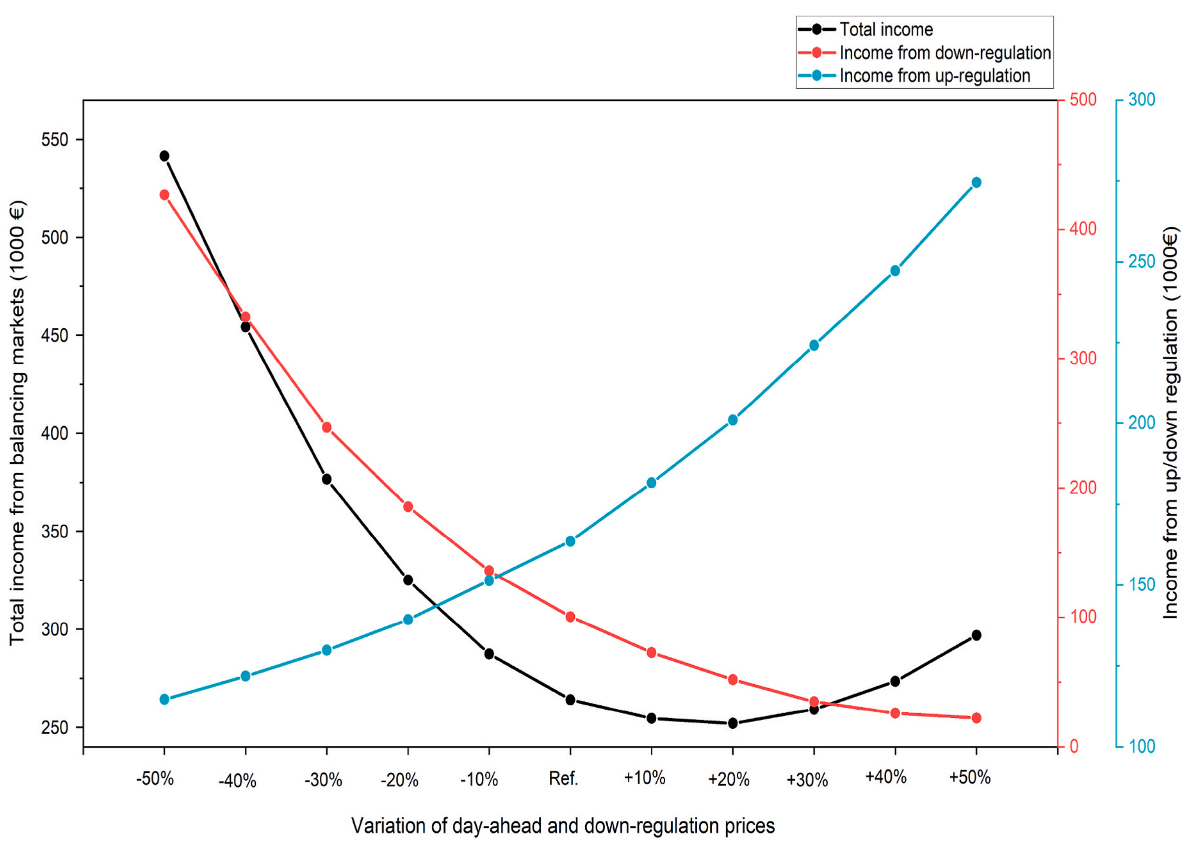

Fig. 9. The variation of revenues from the balancing markets with the variation of day-ahead and up/down-regulation prices.

operation routine is investigated to optimize profit by participating the reserve units in all available marketplaces. The conclusions can be summarized as follows:

- The participation of DHN-connected combined heat and power (CHP) units in balancing markets can be limited due to their restricted ability to adjust electricity production, annual maintenance breaks (typically a couple of months during the summer), and

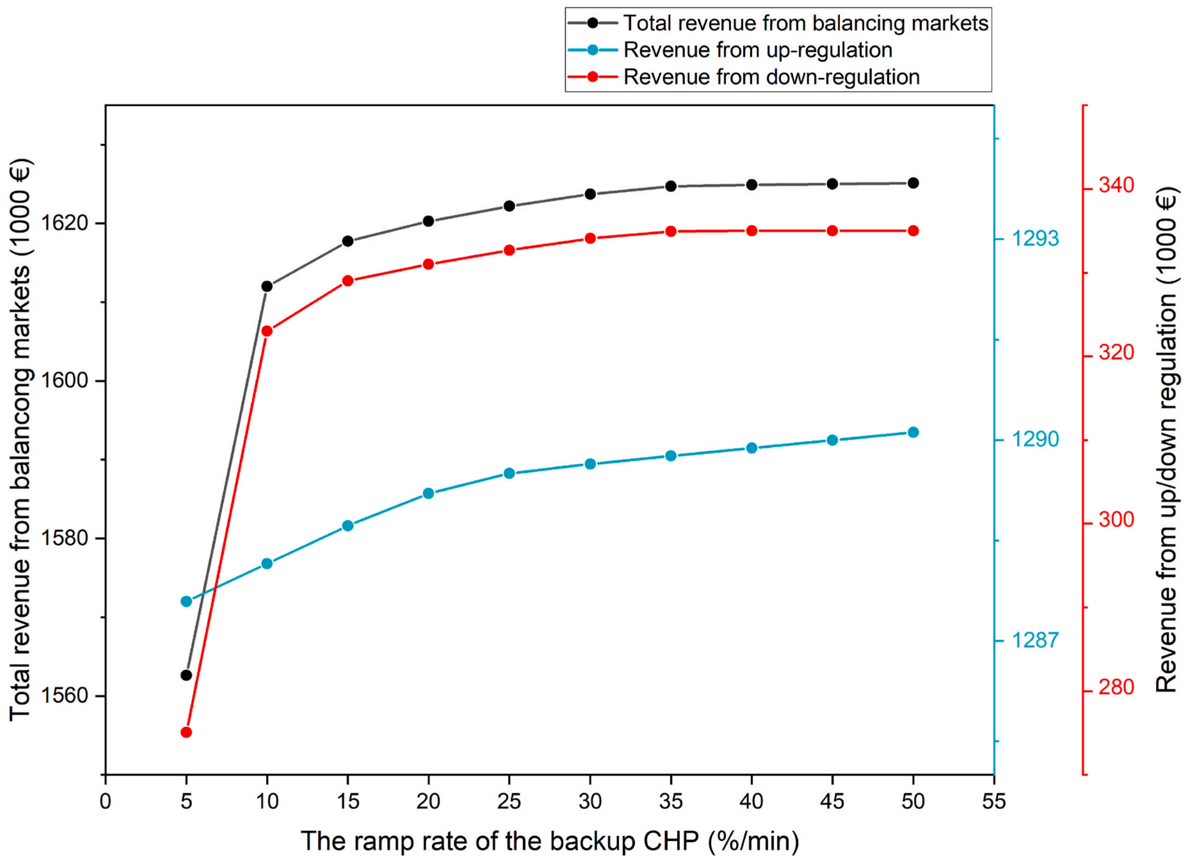

Fig. 10. The variation of revenues from the balancing markets with the variation of the ramp rate of the backup CHP.

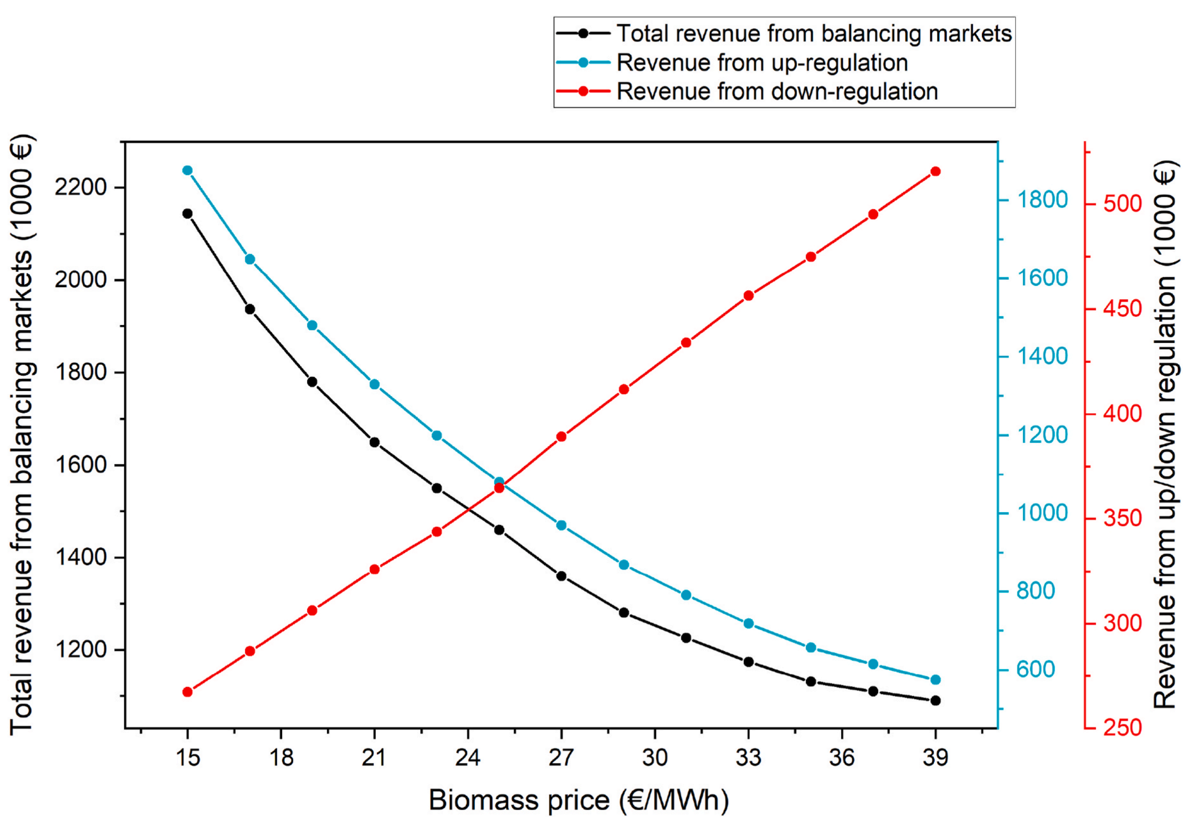

Fig. 11. The variation of revenues from the balancing markets with the variation of biomass price.

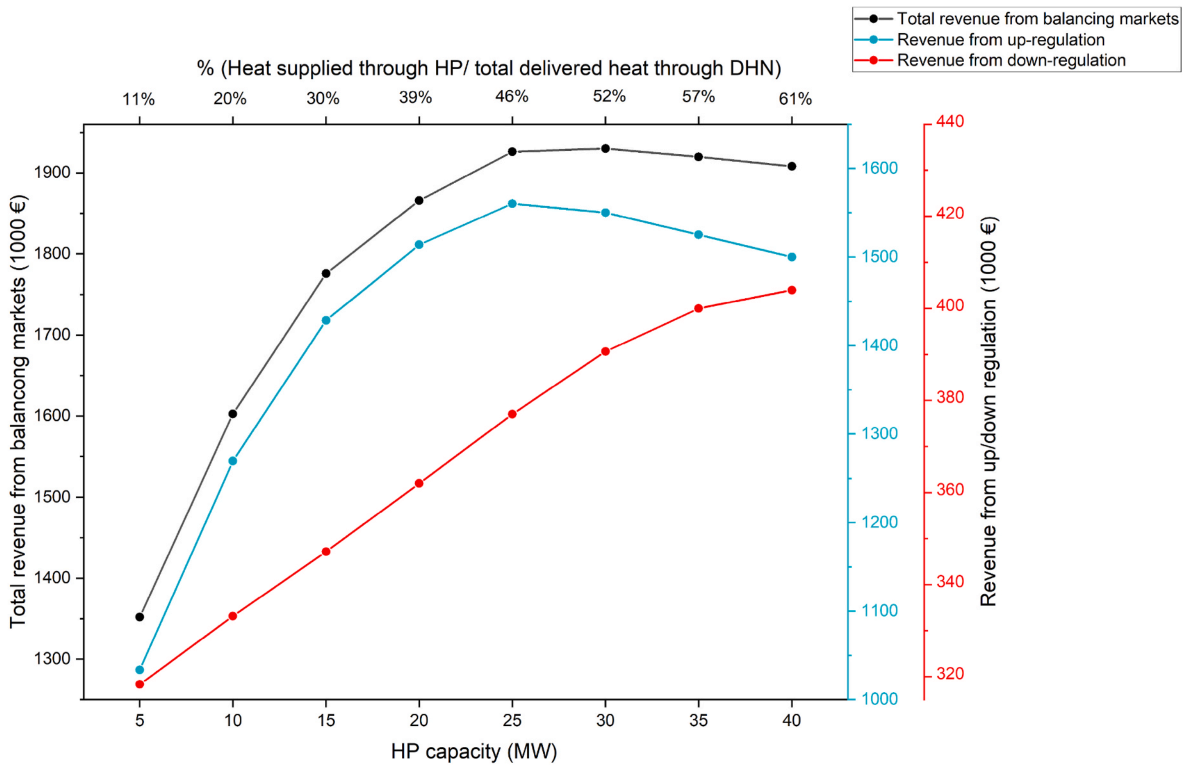

Fig. 12. The variation of revenues from the balancing markets with the variation of electrical capacity of HP. The upper axis indicates the percentage of total heat supplied through HP to the total delivered heat by the DHN.

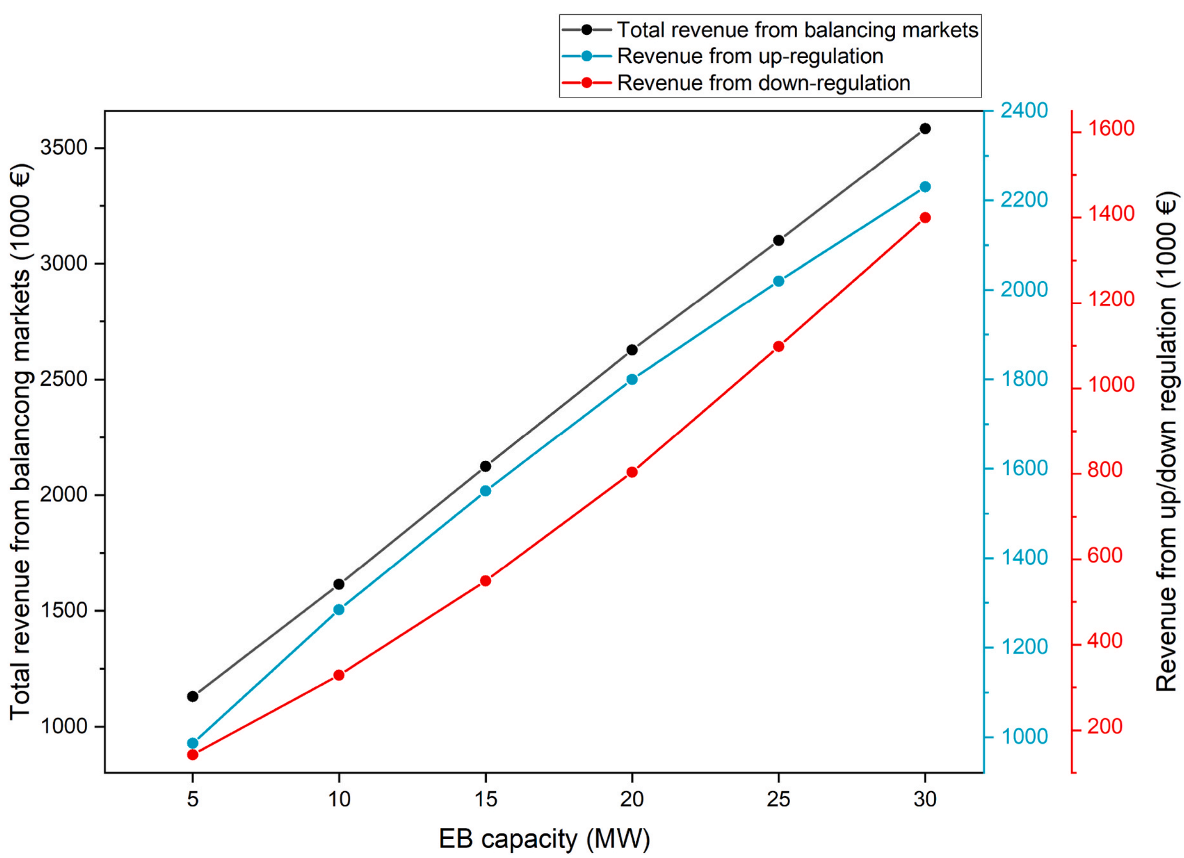

Fig. 13. The variation of revenues from the balancing markets with the variation of EB capacity.

the complexity of providing the rapid response required for balancing provision.
- According to the literature and industry reviews, the best balancing market option for MW-sized-DHN-connected HPs using current technologies is the automatic frequency restoration reserve (aFRR) market, which allows a relatively long activation time (5 min), whereas an EB can participate in other markets such as frequency containment reserve (FCR) and fast frequency reserve (FFR), due to its rapid response time.
- The studied operation routine described in this study provides economic benefits to the DHN operator. This advantage could account for up to 0.4–3.0% percent of all heat sales and 1.3–9.7% of the total electricity sales of the investigated DHN in 2019–2021. Additionally, the proposed routine can boost revenue and thus help the DHN operator avoid economic losses associated with decreased electricity sales from CHP units during low electricity prices.
- Up-regulation yields more profit, particularly in years with higher electricity prices, such as 2021. Down-regulation has considerable benefits in years such as 2020 with low electricity prices.
- Several parameters, including electricity spot prices, fuel price, and physical characteristics of the units such as capacity, minimum running load, and ramp rate, affect the revenue from balancing markets. The optimum electrical capacity of the HP is determined to be 25–30 MW for the studied DHN.
- As discussed in this study, there can be considerable economic benefits for district heat operators to participate in the balancing markets and provide ancillary services to the electrical power system. The possible impact of widespread uptake of DHN-related sector coupling on balancing markets would be increasing the number of players in different balancing markets, paving the way for more competitive prices and higher power quality.
- Electricity markets are moving toward a 15-min resolution, and district heat companies must also prepare their electricity market participation at 15-min intervals in the near future. Also then, participation in the balancing markets may bring further income opportunities.

Author contribution

N. Javanshir: Conceptualization, Methodology, Data curation, Software, Investigation, Writing - original draft, Review & editing, Validation, Visualization. S. Syri: Conceptualization, Supervision, Review & editing, Project administration, Funding acquisition. S. Tervo: Data curation. A. Rosin: 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.126423.

Appendix A

Table A 1
A summary of different studies about the provision of reserve by HPs and EBs.

Study	Country	HP size (MW)	Aggregator	EB size (MW)	Day-ahead	Intra-day	FRR	aFRR	mFRR	FCR generally	FCR-D	FCR-N
[46]	Germany	–	–	1000	✓	–	–	–	–	–	–	–
[41]	Denmark	0.8	–	–	–	–	–	–	–	–	–	✓
[22]	Denmark	0.8	–	0.2	✓	–	–	–	–	–	–	–
[22]	Denmark	12–16	–	3–5	–	–	–	✓	–	✓	–	–
[29]	Denmark	75	–	75	✓	–	–	–	–	–	–	–
[27]	Austria	0.224/0.1	✓	–	✓	–	–	✓	✓	–	–	–
[55]	Denmark	–	–	2.4	✓	–	–	–	–	–	–	–
[28]	Norway	10	–	5	✓	–	–	–	–	–	–	–
[30]	Germany	13.8	✓	–	–	–	✓	–	–	–	–	–
[56]	Norway	–	–	15	✓	–	–	–	–	–	–	–
[12]	Finland	varying	–	–	✓	–	–	–	–	–	–	–
[57]	Denmark	12	✓	3	–	–	–	✓	✓	✓	–	–
[40]	Denmark	0.8	–	0.2	–	–	–	–	–	–	–	✓
[58]	Netherlands	10	✓	–	–	–	–	–	–	✓	–	–
[59]	Germany	0.3	✓	–	–	–	–	–	–	–	–	–
[60]	Denmark	varying	–	varying	✓	–	–	–	–	–	–	–

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