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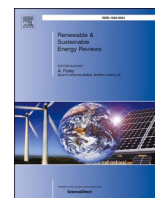
The role of district heating systems to provide balancing services in the European Union

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ABSTRACT

European electricity markets ensure the matching between supply and demand at all times. Due to their time-scale operations, the balancing markets are the last resources to achieve so and ensure the grid frequency. The increasing shares of non-dispatchable power capacities intensify the demand for flexibility. District heating systems (DHs) are potential sources of flexibility if interface technologies are in place like CHP or power-to-heat, together with thermal storage. This study assesses the technical potential of DHs to contribute to frequency containment reserves (FCR), automatic and manual frequency restoration reserves (aFRR and mFRR) markets. Through a review of case-studies, we gain insight and derive appropriate assumptions to estimate the potential at country and EU levels. Based on the POTEnCIA Central scenario up to 2050 — a description of the evolution of the EU energy system with the assumption of no further policies introduced beyond 2017 —, we find that the potential is highest for the provision of aFRR, followed by mFRR and FCR. Specifically, the aFRR technical potential is currently 32 GW — 4 times the aFRR contracted in 2019 in the EU — and it only slightly decreases by 2050. Overall, this study highlights the lack of data on current (and future) DHs and their variety in size and composition. A sensitivity analysis is performed by examining different scenarios for DHs deployment. This research emphasizes the large untapped potential to exploit flexibility from DHs, however, the evaluation of the actual potential shall be done on a case-by-case basis.

1. Introduction

The energy transition is the transformation of the energy sector from a fossil-based to a net-zero CO_2 system [1]. The power sector is the most advanced among the energy sub-sectors in terms of reducing greenhouse gases (GHG) emissions [2]. Thus, significant attention is given to research on the integration of high shares of variable renewable energy sources (vRES) in the power grid [3]. The large deployment of non-dispatchable power generators (i.e., wind and solar power) intensifies the demand for flexibility [4], defined as the ability of the power grid to cost-effectively respond to expected and unexpected fluctuations in load or generation [5].

Fluctuations in load or generation occur on various timescales [4]. Electricity markets are designed to ensure adequate flexibility to the power grid so that supply matches demand at all times [6]. In the short-term, the transmission system operator (TSO) preserves the grid frequency via balancing markets, which, from a time-scale perspective,

are the last stage for electricity trading before its delivery [7,8]. The balancing markets ensure that some electric capacity (i.e., reserve capacity) is available to supply the required energy flow to preserve the grid frequency at all times [9,10]. The type of reserves contracted across the European Union (EU) are frequency containment reserves (FCR) and frequency restoration reserves — activated automatically or manually (aFRR, mFRR). In case of imbalance, FCR are the first to be activated and, thus, they have the strictest time requirements for activation and for energy delivery. FRR are used to replace FCR so that the latter capacities are available for the following imbalance settlement period (ISP). Balancing reserves can be contracted as upward reserves to offset negative imbalances — supply lower than demand —, as downward reserves to offset positive imbalances — supply higher than demand — or as symmetric reserves — equal upward and downward volumes.

Despite the increasing penetration of vRES in the power generation mix, the future evolution of the balancing markets is uncertain. Some studies expect that vRES will lead to higher balancing requirements due to more frequent and larger grid imbalances caused by these fluctuating

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Abbreviations

aFRR	automatic Frequency Restoration Reserve		HR	Croatia
AT	Austria		HRE	Heat roadmap Europe
BE	Belgium		HU	Hungary
BG	Bulgaria		IE	Ireland
BL	Baseline		InT	Interface technology
CCUS	Carbon capture utilization and/or storage		ISP	Imbalance settlement period
CD	Conventionally decarbonized		IT	Italy
CHP	Combined heat and power		LT	Lithuania
CZ	Czech Republic		LU	Luxembourg
DE	Germany		LV	Latvia
DH	District heating		mFRR	manual Frequency Restoration Reserve
DK	Denmark		MS	Member State
EB	Electric boiler		NL	Netherlands
EE	Estonia		P2H	Power-to-heat
EL	Greece		PL	Poland
ES	Spain		PT	Portugal
EU	Europe		RO	Romania
FCR	Frequency Containment Reserve		RR	Ramp rate
FI	Finland		SE	Sweden
FL	Full load		SI	Slovenia
FR	France		SK	Slovakia
GHG	Greenhouse gas		SoF	Source of flexibility
HP	Heat pumps		TSO	Transmission System Operator
			UK	United Kingdom
			vRES	variable Renewable energy sources

energy sources [11–13]. However, despite the growth of vRES in the past decade in various EU countries, some empirical studies report a decrease in contracted balancing reserves thanks to temporal and spatial adjustments of these markets, e.g., by increasing the time granularity or by expanding the imbalance netting region [14–17]. While the literature consulted offers contradictory views on this matter; it is clear that, under the decarbonisation trend of the power system, some of the existing fossil-fuelled dispatchable power plants are (or will be) decommissioned, jeopardising their role of balancing providers [18–20]. This entails that additional sources of reserve capacities must be found. Overall, it is widely accepted that the balancing markets will remain relevant in the short- and mid-term.

The coupling of the power and heat sectors is a promising strategy to exploit new flexibility options and, at the same time, unlock the large GHG reduction potential of the heat sector. This integration enables high efficiencies and the use of cheaper thermal storage compared to the electric one [21–23]. Regarding storage options, one may argue that power-to-heat conversions are not reversible in the domain of low-temperature heat. This is, electricity can be stored as thermal energy via heat pumps (HPs) or electric boilers (EBs) but such thermal energy cannot be converted back into electricity. However, within the context of the power and heat sector coupling, the power-to-heat conversion serves the purpose of meeting the heat demand while the presence of thermal storage increases the flexibility and the performances of heating systems thus enhancing the advantages of the power and heat sector coupling [24].

In this context, technologies operating at the interface between the two sectors must be deployed. These are power-to-heat (P2Hs) — HPs and EBs — and combined heat and power (CHPs) technologies. P2Hs are expected to play a key role in reducing GHG emissions in the heating sector since renewable electricity can replace fossil-fuel based heating technologies [23,25]. If this additional electricity demand is inflexible, P2H deployment can increase balancing requirements due to the systematic patterns of these loads. Instead, if demand response strategies,

including thermal storage, solutions are implemented, P2Hs may contribute to alleviating this issue [26]. Still, the contribution of P2H to balancing markets is not clear yet as it will depend on the growing rates of these technologies in the coming years. Regarding CHPs, they currently generate most of the centralized heat [27,28]. CHPs provide the advantages of high efficiencies and dispatchability, however their role in a decarbonized energy system is not clear yet for two reasons; first, CHP plants are often operated following heat demand, which limits their dispatchability to the power system; second, they largely rely on fossil fuels. In regard of dispatchability, thermal storage becomes a key technology to enable a switch of CHP operations from heat-to electricity-following. In regard of CO_2 emissions, natural gas-based CHPs may still play a role during the transition towards a net-zero CO_2 system, especially when replacing fossil-based boilers. However, in a net-zero CO_2 system the deployment of carbon capture, utilization and/or storage (CCUS) or the switch to clean fuels, i.e., biomass or hydrogen, become crucial.

Regarding their application, P2H are either employed in decentralized or centralized installations [23] while CHPs are mainly found in centralized ones [29]. The exploitation of flexibility from small-scale P2H requires capacity aggregation via virtual power plants to bid on electricity markets [26]. On the contrary, district heating systems (DHs) have already larger electric capacities in place. Most importantly, DHs are natural aggregators of heat demand and can set modes of operation that facilitate the incorporation of larger shares of vRES without compromising the comfort of heat consumers through the implementation of centralized thermal storage [30]. For the above reasons, this paper focuses on the provision of short-term balancing services (i.e., FCR, aFRR and mFRR markets) via P2H and CHP technologies feeding DHs.

Looking into the EU DHs landscape, high penetration of DHs is found in northern, central and eastern European countries as a result of cold climate. Of these, Scandinavia has the most state-of-the-art DHs and produces a large stream of literature on DHs [31]. In Denmark, DHs

provided heat to about 65% of the population in 2017 and national authorities recognise DHs as key element to accommodate large shares of vRES and achieve energy targets by 2050 [32]. In Sweden, the largest deployment of large-scale HPs is found. There, the vast experience on integrating the heat and power sectors has been built up over the last decades [33,34]. Still, these HPs only supply less than 10% of the current DH demand [35]. Scandinavia also leads the use of CHPs because of their long experience in centralized heat production [29]. An example is given by the Greater Copenhagen DH that generates around 95% of heat via CHP to supply 220,000 households and where large coal based CHPs are converted to biomass in view of full decarbonisation of the area by 2025 [36]. Lower but growing penetration of DHs is found in southern European countries. An example is the supporting mechanism for efficient DHs put in place in Lombardy, a densely populated region in the north of Italy [37]. A few examples of DHs with high degree of integration with the power sector are reported by Galindo et al. [38].

Overall, the advantages of centralized heat production in urban areas are increasingly recognized with new DHs built all over the EU [39]. New or retrofitted DHs are expected to exploit the synergies between the heat and power sectors, which are particularly relevant where high shares of vRES are in place. In this context, some literature provides reviews on these synergies. Ma et al. [40] provide a review of stakeholder's perception on smart DHs to exploit flexibility within buildings. Vandermeulen et al. [41] focus on the exploitation of flexibility within DHs by reviewing types of network control; they identify the provision of balancing services as one of the possible advantages enhanced by advanced network control.

Although there is consensus on the potential to exploit flexibility from DHs, the quantification of this potential is challenging due to the diversity of DHs and energy markets across countries. When considering short-term flexibility, several studies propose simulations, optimisation strategies, field experiments, etc. [42–50]. However, a research gap emerges from the link between the geographical scope of DHs and the balancing markets. On the one hand, DHs are diverse and provide heat at local level; on the other hand, the geographical scope of the balancing markets is at a regional, national and continental levels. Therefore, the potential of DHs for the provision of balancing services requires the combination of such levels, from local to national.

This paper aims to answer the question *to what extent can DHs potentially supply balancing reserve capacities to electricity markets in the EU?* Due to the above-mentioned gap, we first conduct a comprehensive review to draw the necessary assumptions to link the geographical scope of DHs and of the balancing markets and to assess the potential at member state (MS) level.

The paper is structured as follow: Section 2 reports the methods applied throughout the research, Section 3 reports the review carried out and Section 4 the results of EU potential assessment. Furthermore, discussion and conclusions are reported in Sections 5 and 6, respectively.

2. Method

The objective of this study is to estimate the technical potential of DHs to provide balancing services in the EU. Due to the difficulties in drawing comprehensive assumptions at the EU level, we first conduct a review of case-studies on DHs that participate in balancing markets.

2.1. District heating as a source of flexibility

In this section, we discuss the characteristics of the European balancing markets and the strategies for DHs to provide these services.

The characteristics of the balancing markets relevant for this study are ramping and delivery periods. The *ramping period* refers to the time between the activation of the bid and the operation at the required capacity, the *delivery period* indicates the time during which a certain amount of power output is required. Start-up and shut-down capabilities

also affect the potential capacity that a technology can offer. However, these are not taken into account due to the large variety of operations of DHs, thus enlarging the calculated potential.

Ramping and delivery periods currently differ per EU country [51]. However, TSOs foresee a progressive harmonisation of the balancing products in view of the pan-European platforms.[1] Table 1 provides the characteristics of these products [52,53] that are procured by TSOs for each ISP. Currently, ISPs varies between 15 and 60 minutes but they will be harmonized to 15 minutes before 2025 [10].

Based on these indicators, we classify the components of DHs. Technologies providing adjustable electric capacity — interface technologies (InTs) — should comply with *ramping periods*, while technologies providing flexibility — source of flexibility (SoFs) — should comply with *delivery periods*. Table 2 summarizes the relevant technologies and strategies accordingly.

InTs are the heat generation technologies that interact with the power system: CHPs and P2Hs. They offer part or all of their electric capacity to the balancing markets; CHPs offer electricity *generation* capacity while P2Hs electricity *consuming* capacity — i.e., demand response. If positive imbalances occur — demand lower than supply — CHPs provide downward reserves by decreasing the electricity production if not operating at minimum load; this entails a decrease of heat production in case of a backpressure turbine and a possible change in the power-to-heat ratio in case of an extraction turbine. P2Hs offer downward reserves by increasing electricity consumption if not operating at full capacity. If negative imbalances occur — demand higher that supply — CHPs offer upward reserves by increasing electricity production if not operating at maximum load; this entails an increase of heat production in case of a backpressure turbine and a possible change in power-to-heat ratio in case of an extraction turbine. P2Hs offer upward reserves by decreasing electricity consumption if not operating at minimum load. For CHP, the ramp rates (RRs) determine the amount of electric capacity that can be offered to each balancing market. RRs vary based on the type of technology: gas turbines and internal combustion engines reach RRs of 20% full load (FL)/min while coal-based steam turbines have RRs of about 4%FL/min [54]. For P2Hs, different assumptions apply to HPs and EBs; EBs offer full capacity to all markets [19], while HPs only to aFRR and mFRR due to constraints related to the technology internal processes [55].

In contrast, SoFs do not actively participate in the balancing markets but they enable the decoupling of heat demand and supply by shifting the demand in time, so that the InTs can freely follow balancing requirements without compromising the heat supply. SoFs include (i) InTs, (ii) storage technologies or (iii) other heat generation technologies. (i) includes extraction CHPs that can vary their power-to-heat ratio. (ii) includes passive storage solutions that exploit the inertia of heat stored either in the DHs water or in the buildings' envelope, and active storage that can provide larger capacities. (iii) refers to *technology switch* that is the possibility of switching the heat supply from one technology to

Table 1

Characteristics of balancing reserves harmonized for various EU countries [48, 49].

Reserve type	Ramping period	Delivery period
FCR	30 s	15 min
aFRR	5 min	15 min
mFRR	12.5 min	15 min

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[1] International Grid Control Cooperation (IGCC) for imbalance netting process; Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) for aFRR process; Manually Activated Reserve Initiative (MARI) for mFRR process.

Table 2
Summary of relevant indicators and strategies for DH components to provide balancing services (FL — full load).

Relevant features of standard products	Classification of DH components	DH technologies	Indicators for compliance to standard product	Potential strategies for balancing provision
Ramping period	Interface technologies (InTs)	*CHP*	Ramp-up/down electricity generation [4–20%FL/minute]	Negative imbalance - Increase electricity production
				Positive imbalance - Decrease electricity production
		P2H:	Zero or maximum electricity consumption	Negative imbalance - Decrease electricity consumption
		- HP		
		- EB		Positive imbalance - Increase electricity consumption
Delivery period	Sources of flexibility (SoFs)	*Extraction CHP*	Shifting time (minute)	Vary power-to-heat ratio
		Building inertia	Shifting time (minute)	Increase/decrease supply temperature
		Network inertia	Shifting time (minute)	Increase/decrease supply temperature
		Thermal storage	Shifting time (minute)	Store or use stored energy
		Technology switch	Shifting time (minute)	Increase/decrease heat supplied by a technology not used for balancing

another, if the operations of one InT varies in response to balancing requirements. This solution is relevant in DHs with multiple heat generators.

2.2. Review of district heating systems providing balancing services

This section reports the method applied to carry out the review. The study includes case-studies of existing and potential configurations of DHs offering balancing services found in peer-reviewed articles, conference contributions and grey literature by screening the keywords: *balancing services/market, frequency regulation, grid services, district heating, thermal networks, heat storage, combined heat and power, large heat-pump.* From these studies, we analyzed general information — i.e., studies' objectives, energy markets or geographical scope — and technical features — i.e., electric and heat capacities and RRs of the InTs, balancing capacity, storage size, heat demand —, to identify the characteristics of DHs that enable their participation in the balancing markets by following the categorization of DH components reported in Table 2.

Then, we introduce the indicators *Heat load shift* and *Technology switch* to assess whether different SoFs can be used (and partly to what extent). *Heat load shift* estimates the shifting time allowed by active thermal storage. We calculate this indicator for summer and winter peak loads, and for the total heat generation capacity (*Winter, Summer* and *Total* in Table 4) by dividing the thermal storage capacity by these three quantities respectively (Eq. (1)). The aim is to provide different insight on systems' configuration and their seasonal operations. *Technology switch* refers to the indicator in Table 2 and is represented as a binomial variable that indicates the capability of a DHs to compensate for a disruption of the heat supply by modulating other heat generation technology.

$$Heat\ load\ shift\ [h] = \frac{Thermal\ storage\ [MWh]}{Heat\ peak\ load\ or\ Heat\ generation\ capacity\ [MW]}$$
Eq. 1

More accurate load shift indicators would require a detailed modelling and simulation of DHs' operations. This, however, falls out the scope of this research. Here, our approach underestimates the real flexibility potential of DHs because a dynamic operation analysis will reveal larger flexibility potentials.

2.3. District heating technical potential for balancing services in the EU

In this section, we report the methods applied to estimate the shares of the European contracted balancing capacities that DHs can supply. The volumes of contracted FCR, aFRR and mFRR capacities were retrieved from the ENTSO-E Transparency Platform for the available years (2015–2019) [56] and complemented with 2016 data provided by Ref. [57]. Estimations of future balancing needs were not carried out due to the uncertainties of the development of these markets reported in

Section 1. Therefore, historical balancing requirements are compared to future capacities of DHs. The geographical scope is the EU, excluding Cyprus and Malta because they are disconnected from the EU continental grid [58]. The resolution is at MS level, with Germany and Luxemburg representing a single node.

We calculate the contribution of DHs by applying the definition of technical potential by Kondziella et al. [59] — including physical boundaries of a system, conversion efficiencies and other technological constraints —, together with the assumptions built with the review: it is assumed that DHs are equipped with sufficient SoFs to support a disturbance of the heat supply within the delivery period — i.e., 15 minutes (Table 1). The actual operations of InTs are not taken into account due to the large variety of operations of DHs across the EU thus enlarging the calculated potential.

Based on these assumption, first, we retrieve data on current and future deployment of DHs and InTs in the EU. Only few scenarios are available that provide the capacity of technologies feeding DHs; these are POTEnCIA [60] and Heat Roadmap Europe (HRE) scenarios [61]. The former includes all EU's MS with yearly values from 2000 to 2050; the latter includes the 14 major heat consumers of the EU for a baseline scenario — 2015 — and three future scenarios — 2050. Due to its completeness, the POTEnCIA Central scenario was chosen for the analysis while the HRE scenarios contribute to the sensitivity analysis.

Second, we calculate the electric capacity of CHPs and P2Hs feeding DHs that can provide FCR, aFRR and mFRR. Regarding CHPs, we calculate the maximum technical potential of balancing capacity that a single unit can deliver to the three reserve markets following Eqs. (2) and (3). We retrieve typical RRs for each category of CHPs (*c*), characterized by the type of plant and input fuel [54]. We assumed these equal for upward and downward regulation. Furthermore, we applied the constraint of 40% minimum load — i.e., multiplication by a factor 0.6 in Eq. (3) [62].

$$BC_{c,i,t,r}^{U} = \begin{cases} x_{c,i,t,r} & if\ x_{c,i,t,r} \le Unit\ size_{c,i,t} \\ Unit\ size_{c,i,t} & if\ x_{c,i,t,r} > Unit\ size_{c,i,t} \end{cases}$$
Eq. 2

$$x_{c,i,t,r} = Unit\ size_{c,i,t} \cdot Ramp\ rate_c \cdot Ramping\ period_r \cdot 0.6$$
Eq. 3

- BC Electric capacity available as balancing capacity [MW]
- U Per unit
- c Category of CHP by fuel and type of technology (shown in Appendix, Fig. 10)
- i EU country
- t Year (2000–2050)
- r Type of reserve — FCR, aFRR and mFRR (see Table 1)
- x Electric capacity available for balancing purposes (different from the plant size) [MW]
- Ramp rate RR characteristics of CHPs [%FL/min] (see Table 2)
- Ramping period Time to deliver full balancing energy [min] (see Table 1)

Next, we calculate the total balancing capacity available per MS, year and type of reserve, as shown in Eq. (4). We introduce the factor *s* to exclude industrial CHPs because POTEnCIA does not distinguish between sectorial applications. Then, *s* represents the share of CHPs feeding DHs that we assume equal to the share of centralized heat consumed by residential and commercial users[2] to the total centralized heat produced [28]. It should be noted that commercial users include facilities such as hospitals, equipped with CHPs that are not connected to DHs. Nevertheless, this assumption can be offset by some industrial CHPs connected to DHs.

$$BC_{i,t,r}^{T} = s \cdot \sum_{c} \left(BC_{c,i,t,r}^{U} \cdot Number\ of\ units_{c,i,t} \right) \qquad \text{Eq. 4}$$

- T Total
- s Share of centralized produced heat consumed by residential and commercial users

Regarding P2Hs, POTEnCIA provides electricity inputs in DHs without distinction between technologies used. To disaggregate the electricity inputs between HPs and EBs, we start from the residential heat load distribution over the available year — 2010 — per MS [63], we normalize the distributions and then we multiply each hour by the annual electricity consumption of DHs per year and per MS. An example is shown in Fig. 1. From the distribution, we allocated to HPs the electricity consumption up to the 95th percentile of the distribution, and we allocated the remaining to EBs because these are normally used as peak generators [36]. Finally, full HPs capacity was assumed potentially available for aFRR and mFRR markets [55], while full EBs capacity for FCR, aFRR and mFRR markets [19].

Lastly, we complete the analysis by summing all the electric capacities of DHs available for balancing and then compared them with the historical balancing reserves contracted by European TSOs, for FCR, aFRR and mFRR.

3. Review of district heating systems providing balancing services

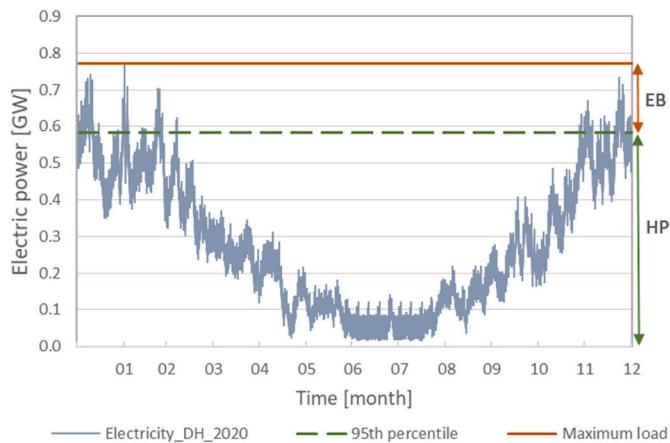This section covers the review on DHs providing balancing services

Fig. 1. Sizing of HP and EB capacities. Electric load distribution of the year — Sweden, 2020.

to make appropriate assumptions to estimate the potential contribution of DHs to balancing services, in Section 4.

The review of these studies highlight the diversity of DHs regarding their composition, size, operating temperature and technology portfolio. Table 3 and Table 4 summarize the objectives, the composition and the operations of the case-studies. About half of these are based on existing DHs, one of which is found to already participate in the local balancing market [38]. Overall, it results difficult to reach unanimous conclusions on the best strategies for DHs to participate in balancing markets because the studies reviewed do not consistently assess all possible operations and conclusions are subject to specific assumptions. Nevertheless, a common characteristic to all these systems arises: the presence of at least one InT and one SoF.

Within the InTs, the presence of CHPs or P2Hs is common to all cases. CHPs size varies from 1 to 250 MW, with balancing capacities ranging from 0.2 to 40 MW and offered either as upward and/or downward reserves [46,47]. If only one type of reserve is offered, normal operations of the plant determine the type — e.g., if the CHP mainly runs at full load, then it is only possible to offer downward reserves, and vice versa). For P2Hs, sizes vary from 0.02 to 12 MW, with all studies offering full P2H capacity to the balancing markets, either as full upward reserve, full downward reserve or half and half, if P2H is running at partial load [47,48,50]. Concerning RRs, they are hardly reported. Still, given their scope, all studies assume that the InTs comply with the requirements of the markets considered.

Moving on to SoFs and delivery periods, the results of *heat load shift* show that even the lowest time shift value is sufficient for balancing provision — i.e., 0.4 h. Due to the lack of data, this indicator is calculated without considering the additional flexibility provided by passive thermal storage, by internal flexibilities of InTs or by technology switch. Still, the calculated time shifts are well above the required thresholds indicating that DHs have sufficient flexibility for balancing purposes.

The possibility of applying technology switch is a relevant solution to increase flexibility, especially for new generation DHs where multiple heat sources are integrated — e.g., renewable sources or waste heat. An example is given by the Danish DHs of Hvide Sande analyzed by Blanco et al. [49]. This system consists of a variety of heat generation technologies including two small CHPs, a solar thermal collector, two back-up gas boilers and an EB that, using locally produced wind power, provides balancing services. The system also includes 180 MWh thermal storage that allows a heat load shift of about 21 and 14 h, in summer and winter respectively. The hour shift calculated over the capacity of all heat generation units is considerably low compared to the hour shift calculated over the winter or summer heat load, as reported in Table 4. This indicates the presence of overcapacity for heat generation. This configuration primarily supports the exploitation of renewable sources but it also facilitates the participation of the CHPs and the EB in the balancing markets because potential rises or drops in the heat generated by these units can easily be compensated by modulating another heat generation technology in the system.

A factor that may influence the ability of a system to provide balancing is the seasonal variation of space heating demand. Based on the *heat load shift* indicator shown in Table 4, in summer these systems provide higher flexibility than in winter — i.e., higher heat load shift hours. In some case-studies, such as in Blanco et al. [49], more balancing energy is provided in summer thanks to larger available capacity thanks to a less constraining heat demand. This feature is not observed in other DHs, sometime, because the plants are switched off in summer. This is the case of Haakana et al. [43], where CHPs are turned off during the summer for maintenance. From the point of view of balancing services, this could affect their contribution since no CHP capacity is available during the summer season. Similarly, when heat demand is at its winter peak all heat generation technologies are expected to operate at full load, limiting their flexibility to address balancing requirements unless some overcapacity is installed. Therefore, intermediate seasons are, in principle, the most favourable period. Still, this is strictly dependent on

Table 3
Contexts, descriptions and objectives of the model-based studies of DH providing balancing services. Notes: 'Balancing (NA)' indicates type of reserve not available.

	[42]	[43]	[44]	[45]	[46]	[47]	[48]	[49]	[50]	[38] – 1 (Taarnby)	[38] – 2 (Jaagerspris)
Objective of the study	Optimal CHP operation strategy for power and heat dispatch – costs minimisation	Optimal CHP operation strategy for power and heat dispatch – profit maximisation	Reserve capacity assessment; operation strategy for CHP – wind curtailment minimisation	Optimal CHP operation strategy for power dispatch – costs minimisation	Optimal CHP operation strategy for power dispatch – profit maximisation	Optimal CHP operation strategy for power and heat dispatch – costs minimisation	Optimal operation strategy for heat pumps – profit maximisation	Optimal operation strategy for DH operators – cost minimisations	Analysis of exergy destruction	Identification of key success factors to the integration of RES and waste heat in DH	Identification of key success factors to the integration of RES and waste heat in DH
Markets analyzed	Day-ahead, Balancing (NA)	Day ahead, Intra-day, Balancing (FCR)	Balancing (NA)	Day-ahead, Balancing (NA)	Day-ahead, Balancing (mFRR)	Day-ahead, Balancing (NA)	Day-ahead, Balancing (aFRR)	Day-ahead, Balancing (NA)	Balancing (NA)	None	None
Geographical scope	Denmark	Finland	China	NA	Germany	NA	Austria	Denmark	Denmark	Denmark	Denmark
Existing DH system	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
System description	Large DHs supplied by multiple CHPs. The operations of a backpressure and an extraction CHP plant with thermal storage are analyzed for balancing purposes.	DHs supplied by a small CHPs that exploits storage capabilities of the thermal network (passive storage).	Large DHs supplied by multiple CHPs. The operations of a backpressure and an extraction CHP plant with thermal storage are analyzed for balancing purposes.	DHs supplied by a small CHP and heat storage. Sector integration with the gas sector is included.	DHs supplied by gas-fired CHP with thermal storage.	DHs mainly fed by CHP, retrofitted with an electric boiler. The system exploit the thermal inertia of buildings (passive storage).	DHs supplied by biomass boilers partly at the end of their lifetime. Their substitution with heat pumps is analyzed.	DHs with CHP, EB, solar thermal and two back-up gas boilers.	Small DHs supplied by a heat pump. An electric boilers is used to boost the water temperature after storage. Balancing is only provided by the heat pump.	DH and cooling system supplied by 4 reversible HP using wastewater. The system is connected to the Greater Copenhagen DH.	Small, multi-sourced and low carbon consumer-owned DH.

specific DHs. For instance, Taarnby DH is equipped with reversible HP that provide heat in winter and cooling in summer, thus they operate throughout the whole year [38].

The case-studies presented focused specifically on the provision of balancing services, hence the required flexibility for each case was known beforehand. However, without this information, it is challenging to define whether adequate sources of flexibility are available in existing DHs at MS level. Table 5 reports values found in literature of active and passive storage ability of all Danish DHs and partial values for Sweden and the DHs in Helsinki. The *heat load shift* calculated over the annual average daily heat demand is at least 1 h for all data available, including passive storage of all Danish DH networks, thus sufficient for balancing services. However, due to their exposure to seasonality and the lack of data for other countries, these values may increase or decrease along the year or vary between each specific DHs based on their sizes.

From the review, the following assumptions are applied to estimate the technical potential contribution of DHs to balancing services at EU level. These are:

1. The flexibility available within DHs is assumed to be sufficient to provide balancing in all DHs for the duration of the delivery period.
2. The ramping periods of FCR, aFRR and mFRR markets constraint the balancing provider, thus the RRs of CHP and P2H are the only limiting factor for the provision of balancing services since actual operations of DHs are not taken into account.

4. DH potential for the provision of balancing services in the EU

This section reports the results of the technical potential of DHs to provide FCR, aFRR and mFRR balancing reserves in the EU.

The POTEnCIA Central scenario is calibrated with the Eurostat database up to 2015. From 2000 to 2015, the heat supplied by DHs in the EU sees a constant trend and accounts for about 6% of the total heat, with large disproportions between MS — e.g., the share reaches 32% in Denmark while in Spain is 0% [28]. From 2015 to 2050, POTEnCIA foresees an overall growth of the heat delivered by DHs of about 40%, as shown in Fig. 2 — red line. Nonetheless, this corresponds to a share below the 10% of total heat [60].

In 2020, heat generation from CHPs accounts for almost 70%, while P2Hs only produce about 1% of the heat supplied by DHs [28]. Accordingly, almost all of the DHs potential for balancing derives from CHPs — blue areas in Fig. 2. However, the expected electrification of DHs in the coming years may change the picture leading to a larger utilization of P2Hs. In 2050, P2H capacity is expected to be over 6 times larger than in 2020; meanwhile, while CHP capacity is expected to decrease by about 27% [60]. Nonetheless, due to the very low share of P2Hs in DHs in 2020, the growing P2H capacity does not fully compensate the decreasing CHP capacity, which remains in 2050 the largest potential provider of balancing services within DHs. The additional heat generation of the growing DHs in the EU is expected to derive from other sources not connected to the power grid.

The bars in Fig. 2 represent the historical upward balancing reserves contracted by the European TSOs under consideration. The size of contracted reserves is lower than the potential of DHs, which reaches, in 2019, 141% of the symmetric FCR contracted by the TSOs that year, 381% of the upward aFRR and 166% of the upward mFRR. The analysis on the downward reserves shows similar results because the same values have been assumed for up and down RRs; these are shown in the Appendix, Fig. 11. The electric capacity of DHs — blue line — decreases towards 2050 because of the expected decommissioning of large coal-based CHPs — Fig. 10 in the Appendix. This affects the mFRR potential that includes 60% of the total CHP capacity available for balancing — i.e., light blue stacked area follows the same trend as the blue line. The aFRR and FCR potentials remain almost unchanged in 2050. Having a more limited ramping period compared to mFRR, the potential of these is built upon the numerous but smaller gas-based CHPs which face a

Table 4

Configurations of DHs providing balancing. Notes: '–' indicates not applicable; 'NA' indicates not available; [a] 2 MW from electric boiler and 8 MW from CHP; [b] includes the total heat generation capacity of the DH system (CHP, P2H, heat-only boilers, solar thermal); [c] the analysis is performed on a typical summer or winter day; [d] calculated by the authors as reported in Section 2; [e] calculated as *Thermal storage/(Annual heat demand/8760)*; [f] the system uses thermal storage of the attached Greater Copenhagen DH.

		Unit	[42]	[43]	[44]	[45]	[46]	[47]	[48]	[49]	[50]	[38] – 1	[38] – 2
Power sector side	*Generation technologies*	EB	MW$_{el}$	–	–	–	–	–	12	–	6	0.2	–	–
	– Electric capacity	HP	MW$_{el}$	–	–	–	–	–	–	0.04	–	0.2	2	0.2
		CHP	MW$_{el}$	250	6	220	1	106	135	–	7.3	–	–	5.8
	RRs		%FL/min	25	NA	NA	10	NA	NA	NA	NA	NA	NA	NA
	Balancing capacity	Up	MW$_{el}$	30	4	40	0.2	0	20[a]	0.02	NA	0.1	NA	NA
		Down	MW$_{el}$	30	2	40	0.2	65	0	0.02	NA	0.1	NA	NA
District heating side	*Generation technologies*	Total[b]	MW$_{th}$	–	15	230	1	115	102	3.4	44.3	1.0	6.7	20.1
	– Thermal capacity	EB	MW$_{th}$	–	–	–	–	–	12	–	6	0.2	–	–
		HP	MW$_{th}$	–	–	–	–	–	–	0.2	–	0.8	6.7	1
		CHP	MW$_{th}$	330	15	230	1	115	90	–	9.3	–	–	7
	Thermal storage	Active	MWh	500	–	90	0.9	480	–	3.7	180	4.2	NA[f]	140
		Passive	MWh	–	NA	–	–	–	NA	–	–	–	–	–
	Heat peak demand	Winter	MW$_{th}$	450	15	NA	-[c]	NA[c]	85	NA	12.3	0.8	NA	NA
		Summer	MW$_{th}$	200	-[c]	NA	0.3	–	-[c]	NA	8.5	NA	NA	NA
	Annual heat demand		GWh	1500	NA	NA	NA	NA	NA	6.5	NA	2.1	50	39
	Heat load shift[d]	Total	hours	–	–	0.4	0.9	4.2	–	1.1	4.1	1.4	–	–
		Winter	hours	1.1	–	–	–	–	–	5.0[e]	14.6	17.3[e]	–	–
		Summer	hours	2.5	–	–	2.7	–	–	5.0[e]	21.2	17.3[e]	–	–
	Possibility for technology switch			No	No	No	No	No	Yes	Yes	Yes	Yes	No	Yes

Table 5

Heat load shift capacity of DHs. Notes: [a] thermal networks heat accumulation capacity; [b] it indicates the assumed increased temperature in the DH network that provides passive thermal storage; [c] calculated by the authors as reported in Section 2.

Geographical scope	Country	Denmark	Sweden	Finland
	DHs	DK all systems	SE all systems	90% heat Helsinki
Sources		[64,65]	[66,67]	[68,69]
Annual average daily heat demand	GWh	115	156	17–20
Passive storage[a]	GWh	5		1.2
ΔT[b]	K	10		15
Annual average heat load shift[c] – passive s.	**Hours**	**1**		**1.4–1.7**
Active storage	GWh	50	42	
Annual average heat load shift[c] – active s.	**Hours**	**10**	**6**	

Fig. 2. Technical potential of DH electric capacity available in the EU25 + UK for FCR, aFRR and mFRR balancing, and 95th percentile of the UPWARD balancing reserves contracted by EU TSOs, based on POTEnCIA scenario up to 2050. The potential for aFRR includes the one for FCR and the mFRR potential the previous two (mFFR ⊂ aFRR ⊂ FFR) based on the ramping period constraints.

lower decline in 2050 than coal-based technologies.

Fig. 3 shows the results on a country basis. It is evident how the deployment and the evolution of DHs largely vary between countries. Denmark, Sweden and Finland already have in place large amounts of DHs, thus, they present relatively low grow in future years. Central European countries such as Germany, Austria and France see a large deployment of DHs while in southern countries they remain limited. Instead, eastern European countries expect a decrease in the heat supplied by DHs. This is probably caused by the renovation of old DHs that currently present high thermal losses. Thus, their update is expected to lower the overall centralized heat generation. Many countries show large variation in the balancing potential over time. There are caused by non-synchronized CHP fuel shifts (i.e., there are periods when a fossil-fuelled CHP is decommissioned but the replacement will start operating some years later). For instance, a peak is notable around 2040 in some countries (e.g., DE, DK, LV, HR). Then, POTEnCIA foresees an uptake of CHP fed by biomass and/or synthetic gases.

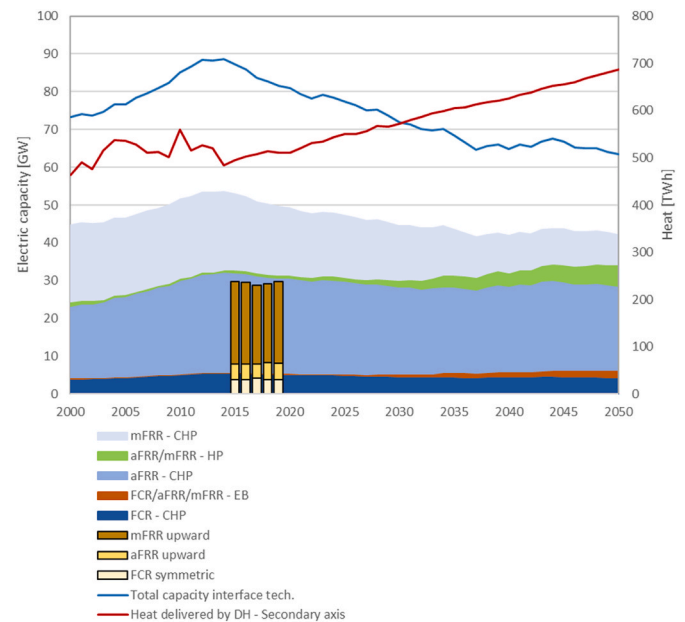Lastly, P2Hs in DHs are expected to gain importance only in some countries, such as in Sweden and France. There, the cheap electricity produced from nuclear power plays a role. Overall, these results emphasize how market conditions impact the deployment of the InTs, thus the capacity available for balancing markets. It can be said that the technical potential of EU DHs to provide balancing capacity is high, with
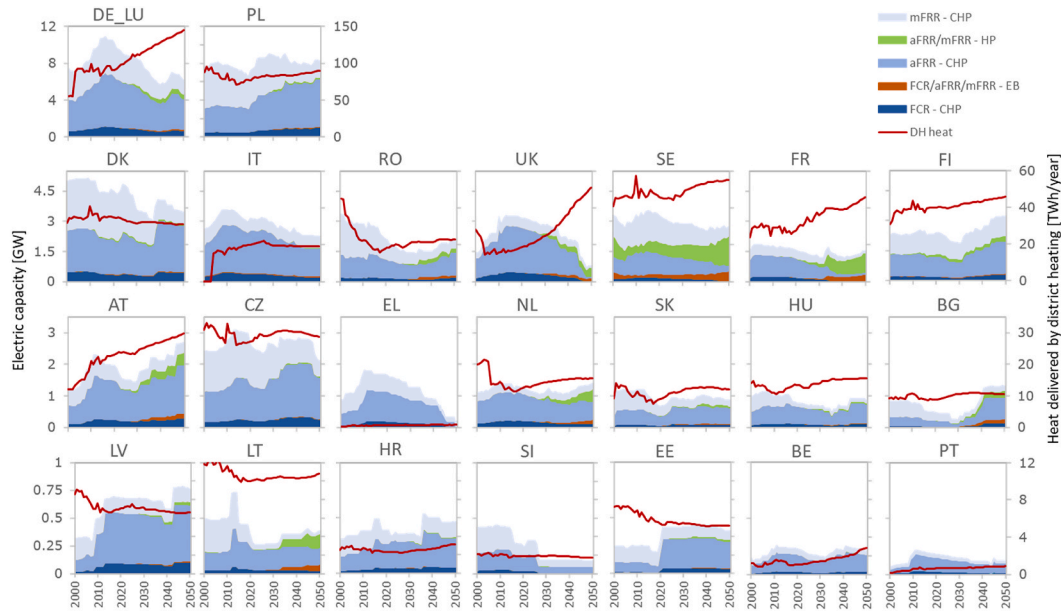
Fig. 3. Technical potential of DHs electric capacity available for FCR, aFRR and mFRR markets per country based on POTEnCIA scenario. ES and IE are not represented because the scenario foresees no DH deployment in these countries. The potential for aFRR includes the one for FCR and the mFRR potential the previous two (mFFR ⊆ aFFR ⊆ FFR) based on the ramping period constraints.

variations between countries. However, practical issues such as seasonality and flexibility of the heat supply should be accounted for by each individual DH operator.

5. Discussion

This research highlights the limited progress in the coupling of DHs with the power sector for balancing services. Even though some successful cases have been identified, their current contribution as sources of flexibility, and as balancing providers in particular, remains limited. The expected integration of the power sector with energy consuming sectors may enable additional opportunities for DHs, but also brings forward other solutions for balancing provision; electric vehicles and decentralized HPs are, for instance, gaining interest on this matter [70, 71] because they are suitable to provide short-term flexibility when their capacities are aggregated under virtual power plants. However, based on their small-scale sizes and patterns of use, the provision of long-term flexibility becomes difficult. In contrast DHs, taking advantage of their larger sizes and of thermal storage technologies, can offer flexibility on a

longer time-frame — e.g., intraday. Some studies report that, with long-term thermal storage solutions in place, DHs may become optimal candidates to provide seasonal flexibility to a highly renewable power system [24]. Nevertheless, our study shows that DHs offer high potential for short-term flexibility, in most cases without the need for any technological upgrade, e.g., by exploiting existing thermal storage or system inertia. Still, full flexibility exploitation often requires the deployment of smart technologies [24].

It is important to note that our results are highly dependent on the chosen scenario, namely the POTEnCIA Central scenario. Therefore, we performed a comparative analysis with the HRE scenarios, which cover 14 EU countries for the years 2015 and 2050 [61] — POTEnCIA's results, which cover all EU countries, have been scaled accordingly to make both sources comparable. Fig. 4 compares POTEnCIA's 2015 and 2050 results with HRE baseline in 2015 — BL2015 — and with three 2050 scenarios — BL2050, CD2050, HRE2050. BL2050 represents the evolution of the energy system under current policies, CD2050 assumes renewable goals without infrastructural changes in the heat sector and HRE2050 envisions a redesigned heat sector, hence the drastic increase
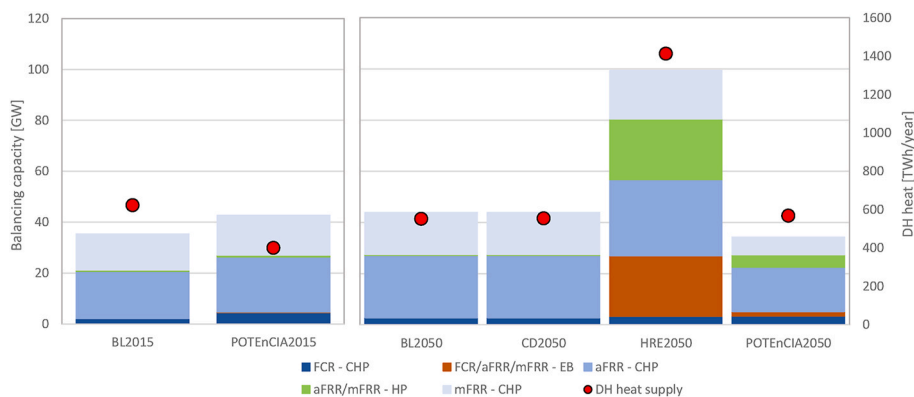

Fig. 4. Sensitivity analysis on the scenario applied by including POTEnCIA and HRE scenarios.

of heat supplied by DHs — red dots, secondary axis — and of P2Hs. The heat delivered by DHs foreseen by the POTEnCIA Central scenario in 2050 is in line with the 'conservative' scenarios of HRE — BL2050, CD2050. However, CHP capacity does not decrease in 2050 in the latter scenarios but the increase of potential from 2015 to 2050 is attributable to the increase of fast capacities in the CHP's fleet. Instead, the POTEnCIA scenario foresees a decrease of CHPs in 2050 and a slight uptake of P2Hs. Overall, POTEnCIA results show the lowest technical potential for provision of balancing service; still, these are more than sufficient to cover the EU requirements.

All the scenarios described foresee a relevant role for CHPs in 2050. However, the most recent developments on CO_2 emission reduction targets entail a net-zero system by 2050 [72]. Thus, the role of CHPs in such energy system is strictly dependent on the advancement of sustainable fuels and/or CCUS. Furthermore, the future role of P2Hs in DHs depends on policies and markets development.

Beyond the uncertainties on the future of the InTs, the study presents limitations in the methods applied. These arise from the scarcity of data available related to DHs, both in terms of flexible capacity — i.e., available storage capacity — and of the InTs in place. The uncertainties on the fuels to feed CHPs may vary the future composition of the CHP fleet, thus varying their RRs. Therefore, we performed a sensitivity analysis by applying two extreme cases: all CHP fleet is composed by technologies with (i) high RR — 20%FL/min — or (ii) low RR — 4%FL/ min. The stacked areas in Fig. 5 represent the original calculations while the lines show the potential calculated with high and low RR for each market. For mFRR, the potential is unchanged because varying the RRs still allows the total exploitation of CHP capacity for balancing. For aFRR, CHPs provide full capacity with high RRs, but the potential strongly decreases with low RRs: this is halved in 2050 when the reference case has a larger share of CHPs with fast RRs. Nevertheless, also the worst case has sufficient potential to satisfy all aFRR requirement of 2015–2019. Similar results apply to FCR.

Regarding the calculations on P2Hs, the main limitations of the study are the only utilization of the 2010 heat load distribution and the assumption that peak c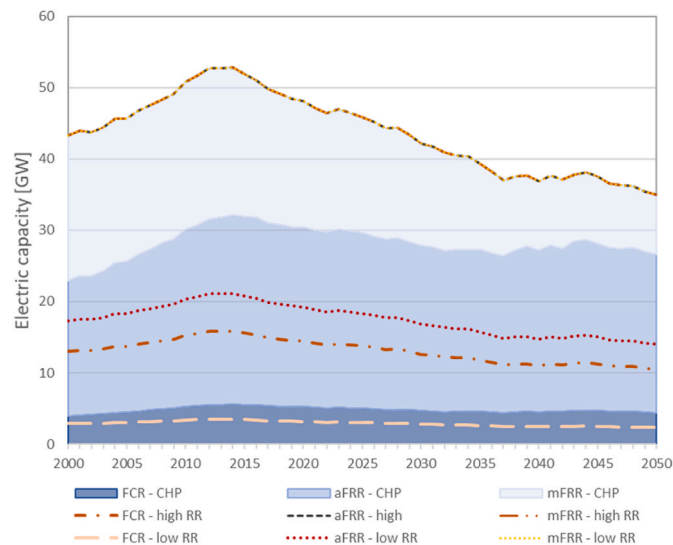apacity — i.e., EBs — satisfies 5% of the heat peak demand. Regarding the former, more recent and comprehensive data were not found for all MS. Regarding the latter, we have performed a sensitivity analysis over the percentile applied to define HP and EB capacities. We have varied this from the 90th to the 99.5th percentile, thus assuming that the peak capacity supplies between 10% and 0.5% of the total heat generated by electricity. Fig. 6 shows that the largest variation of the installed electric capacity occurs in 2050, when these technologies see larger deployment. Between the 95th and 99.5th percentiles, a variation of 1 MW of HP and EB capacities occurs. This corresponds to about 20% variation for HPs and 50% for EBs. However, this only affects the balancing capacity for FCR, since aFRR and mFRR can be supplied indistinguishably by HPs or EBs.

Furthermore, the technical potential we have calculated does not take into account the operational constraints of specific DHs, even though these can strongly constrain it. The operational constraints are dependent on the size and composition of DHs, the seasonal variation of heat demand and the specific strategies put in place by DHs operators. Some examples of these variations were reported in Section 3, with particular emphasis on the different operations that deal with seasonal variations of heat demand. These large variations could result problematic for a constant supply of balancing reserves throughout the year, as requested by most TSOs (Appendix, Fig. 7, Fig. 8, Fig. 9). However, the large potential calculated — well above 100% — can, in principle, offset this issue: the various operations of DHs across the EU allow the contribution to the balancing reserves at all times to a certain extent. Furthermore, the combination of DHs with cooling is becoming more widespread [73] and this could become a great asset to provide constant balancing throughout the year.

Last, it should be noted that we draw the first assumption of Section 3 only based on the active and passive storage data available for Scandinavian countries since no data were found for other MS. The location of a DHs and the seasonality of the heat demand could affect this assumption. However, being the time-frame of the balancing market extremely short (i.e., 15 min), it is reasonable to assume that the inertia of a large enough system is sufficient to allow the disruption of heat supply for that time-frame without noticeably affecting the consumer. Furthermore, operation strategies that exploit passive storage can, in principle, function at any season by regulating the inlet temperature relatively to the nominal operating temperature of supply at any time of the year.
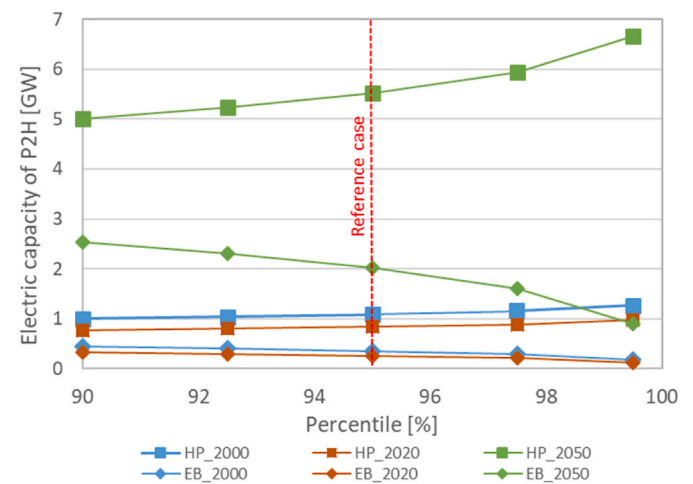

Fig. 5. Sensitivity analysis on the RRs of CHP technologies. 'High RR' indicates a RR of 20%FL/min applied to all types of CHP while 'Low RR' a RR of 4% FL/min.

Fig. 6. Sensitivity analysis on the percentile that determines the HP and EB capacities.

6. Conclusions

This study aims at estimating the technical potential of DHs to provide reserve capacities for balancing services in the EU. Due to the geographical gap between DHs and the balancing markets and the lack of data on DHs in the EU, we first performed a review of case-studies to define proper assumptions. Even though all the case-studies included at least one InT and one SoF, the mode of operations of the DHs greatly differed based on the local conditions, size and composition, heat demand and seasonal variability. Therefore, we drew broad assumptions that shall be verified at the specific DH level.

Our results show that DHs are a valid alternative to provide balancing capacity to the power sector, reaching technical potential well above 100% of the contracted FCR, aFRR and mFRR. CHPs contribute to the 98% of potential in 2020 and 84% in 2050 and P2Hs to the remaining shares. The sensitivity analysis performed on the scenarios shows that only a re-designed heating sector can notably increase P2Hs deployment and that CHPs maintain a relevant role in the future. However, the most recent decarbonisation targets of the EU bring uncertainties to this role.

This study demonstrates that, in addition to their high efficiency and dispatchability, CHPs can significantly contribute to balance the power system by taking advantage of the flexibility within the heating sector. This aspect shall be taken into consideration when designing future energy systems. Regardless of the uncertain growing pace, P2Hs will gain market shares in DHs and, together with thermal storage, increase the balancing potential in the EU. Nevertheless, the calculated potential is subject to the future requirement of balancing capacities that are not considered in this study.

The results of this paper may be relevant for extra-EU countries where DHs are or will be deployed and where the increasing share of non-dispatchable power generators challenges the operations of the power system. Nowadays, Russia and China have the highest shares of DHs followed by the EU [67]. The share of non-dispatchable sources is negligible in Russia [74], however, China faces the same issues as the EU in the search for new sources of flexibility, as shown by the case-study of Zhou et al. [44]. Nonetheless, electricity markets differ across world regions, thus the conclusions of this work may not be transferred directly to extra-EU countries. Further research shall focus on economic aspects of this application, such as the profitability for DH operators to participate in the balancing markets and/or other electricity markets.

Author contributions

Boldrini, A.: Conceptualization, Formal analysis, Writing – original draft / Writing – review & editing, Visualization. Jiménez Navarro, J.P.: Supervision, Validation, Writing – original draft / Writing – review & editing, Visualization. Crijns-Graus, W.H.J: Supervision, Validation. van den Broek, M.A: Supervision, Validation

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.
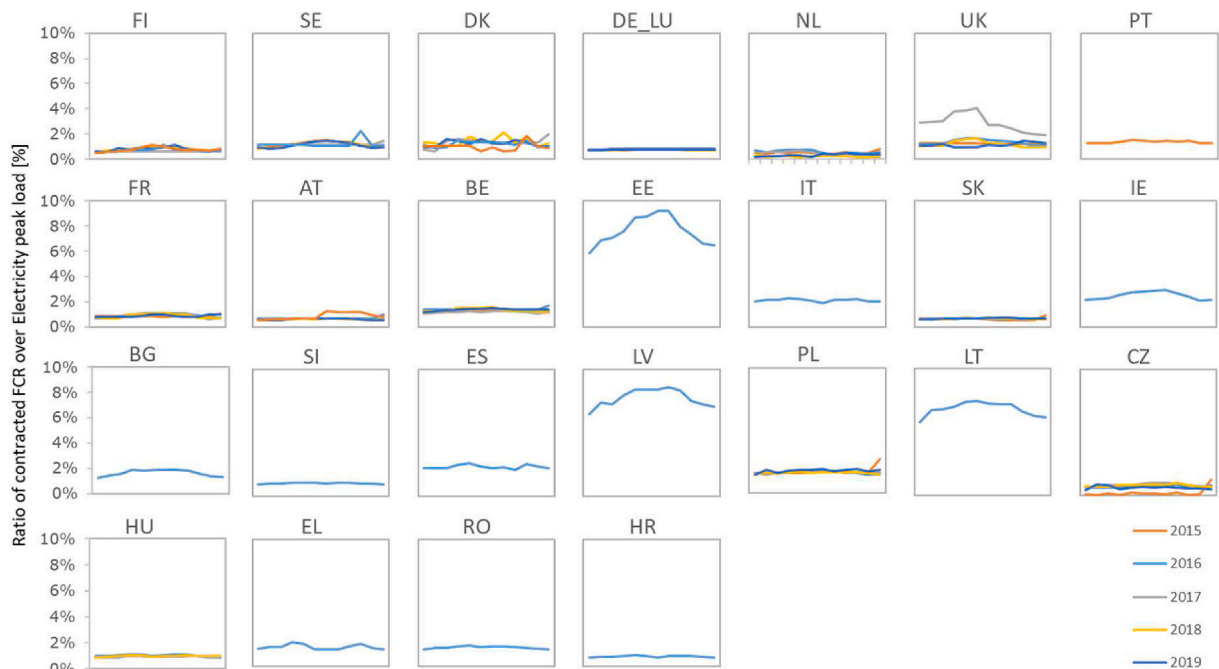
Acknowledgments

Appendix

Fig. 7. Historical data (2015–2019) of the ratio of contracted FCR capacities over electricity peak load, per country (Table 6) [56,57].

Fig. 8. Historical data (2015–2019) of the ratio of contracted aFRR capacities over electricity peak load, per country (Table 6). Empty graphs indicates lack of data [56,57].
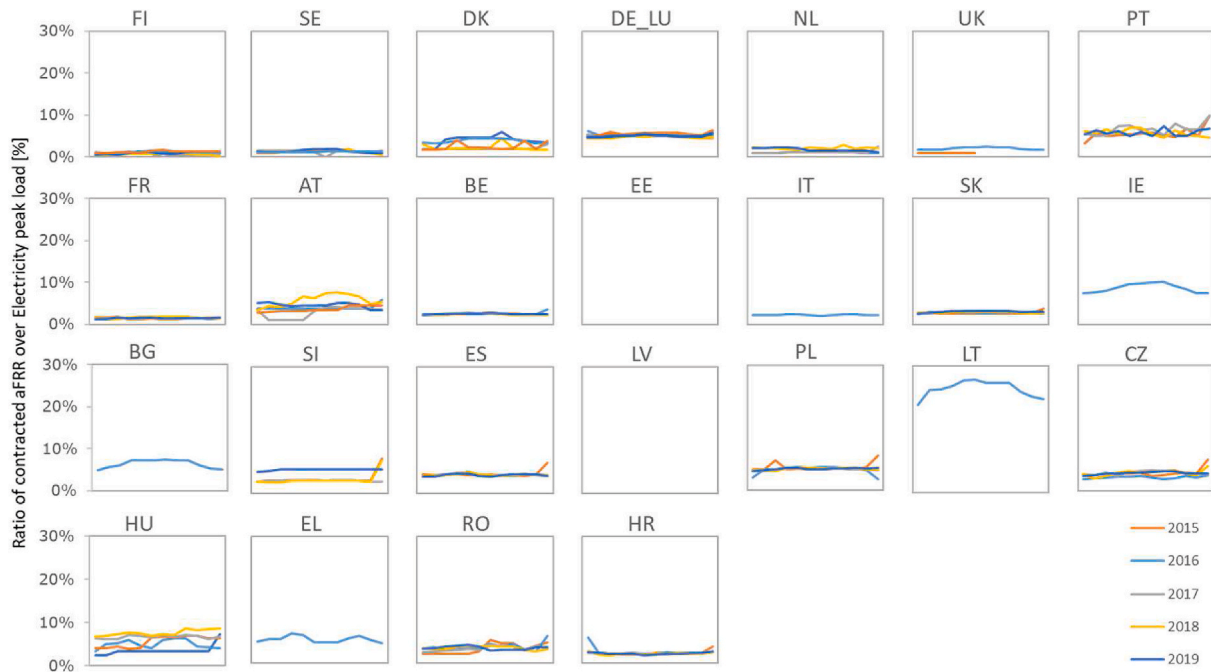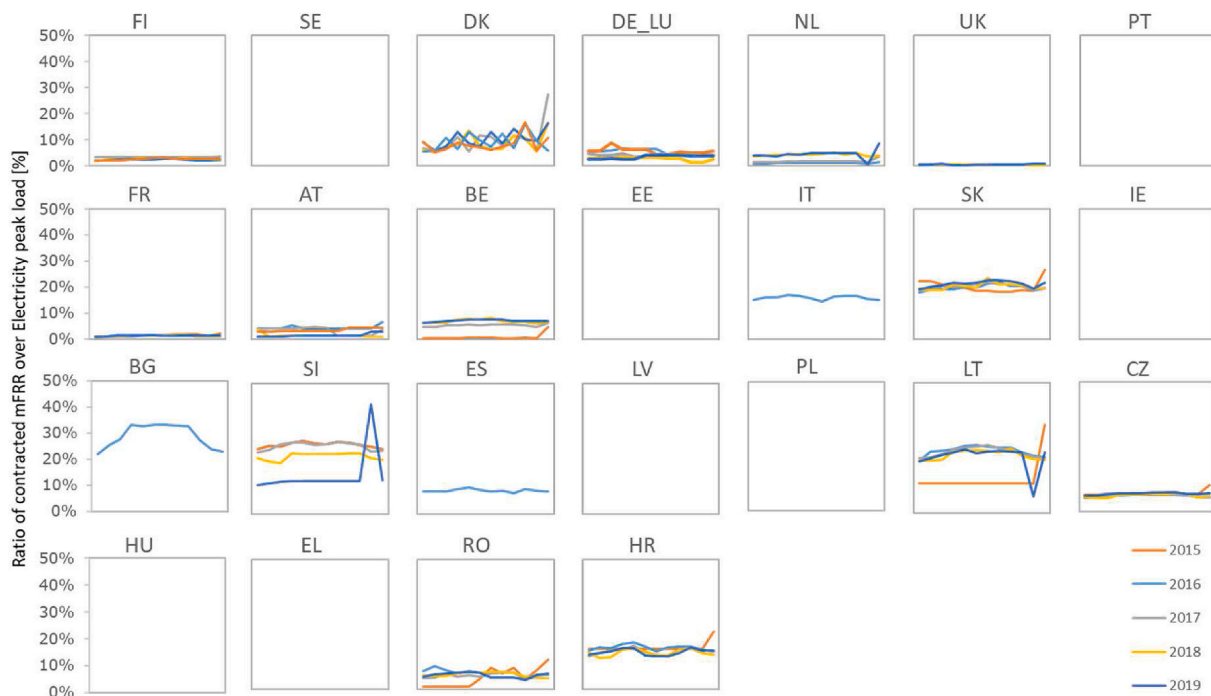

Fig. 9. Historical data (2015–2019) of the ratio of contracted mFRR capacities over electricity peak load, per country (Table 6). Empty graphs indicates lack of data or out of range. The latter are EE – max 100%, LV – max 152% and PT – max 245% [56,57].

Table 6
Electricity peak demand per year (2015–2019) and country [75].

| [GW]	2015	2016	2017	2018	2019
EU28	454.0	522.7	525.8	526.9	505.4
AT	10.6	11.7	11.9	12.1	12.0
BE	11.9	13.1	13.3	13.5	13.6
BG	5.4	7.1	7.7	6.4	6.5
CY	0.8	1.0	1.0	1.0	0.8
CZ	9.3	10.5	10.9	11.1	10.9
DE_LU	80.5	82.1	81.3	81.7	79.1
DK	5.2	6.1	5.9	6.1	5.8
EE	1.2	1.5	1.5	1.5	1.2
EL	8.0	9.2	9.7	9.1	8.0
ES	36.6	40.1	41.0	40.6	40.0
FI	11.6	15.2	14.4	14.1	15.0
FR	70.2	88.6	94.2	96.3	88.5
HR	2.7	2.9	3.1	3.2	3.0
HU	6.0	6.4	6.5	6.6	6.6
IE	4.2	4.7	4.9	4.9	4.2
IT	50.8	56.1	56.6	57.6	57.8
LT	1.7	2.0	1.9	2.0	2.0
LV	1.1	1.3	1.2	1.3	1.2
MT	NA	NA	NA	NA	NA
NL	16.6	18.2	18.6	18.5	18.3
PL	22.6	24.3	24.9	25.0	24.8
PT	7.5	8.7	8.4	8.7	8.6
RO	7.9	8.8	8.9	8.9	8.8
SE	20.2	26.6	26.2	27.4	20.2
SI	2.1	2.1	2.3	2.4	2.3
SK	4.0	4.4	4.5	4.5	4.6
UK	54.7	69.4	63.6	61.4	60.6
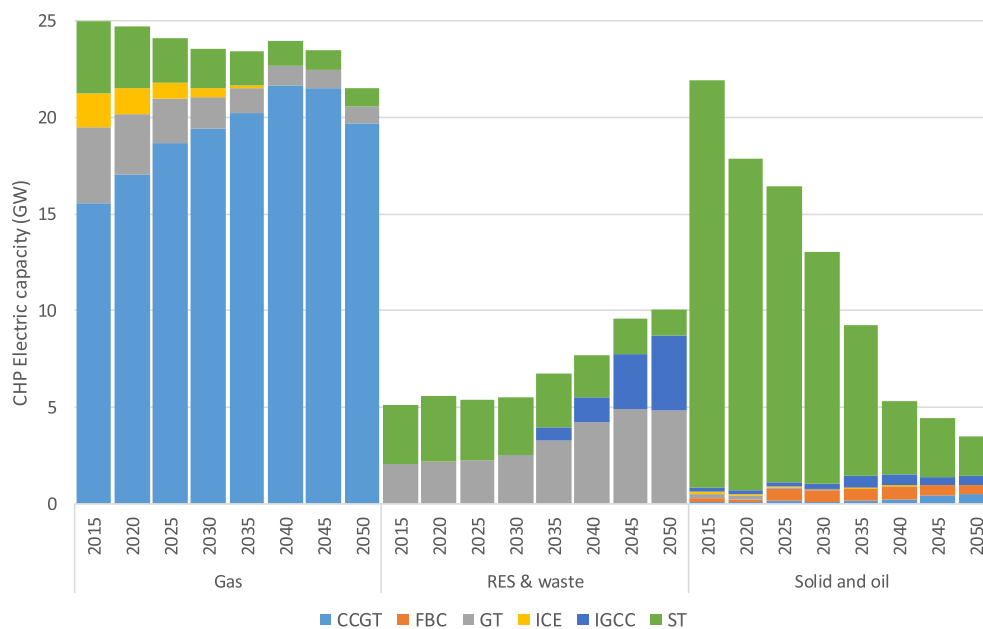
Fig. 10. CHP plants development per type of technology and type of fuel based on POTEnCIA central scenario. CCGT — Gas turbine combined cycle; FBC — Fluidized bed combustion; GT — Gas turbine; ICE — Internal combustion engine; ST — steam turbine [60]. .
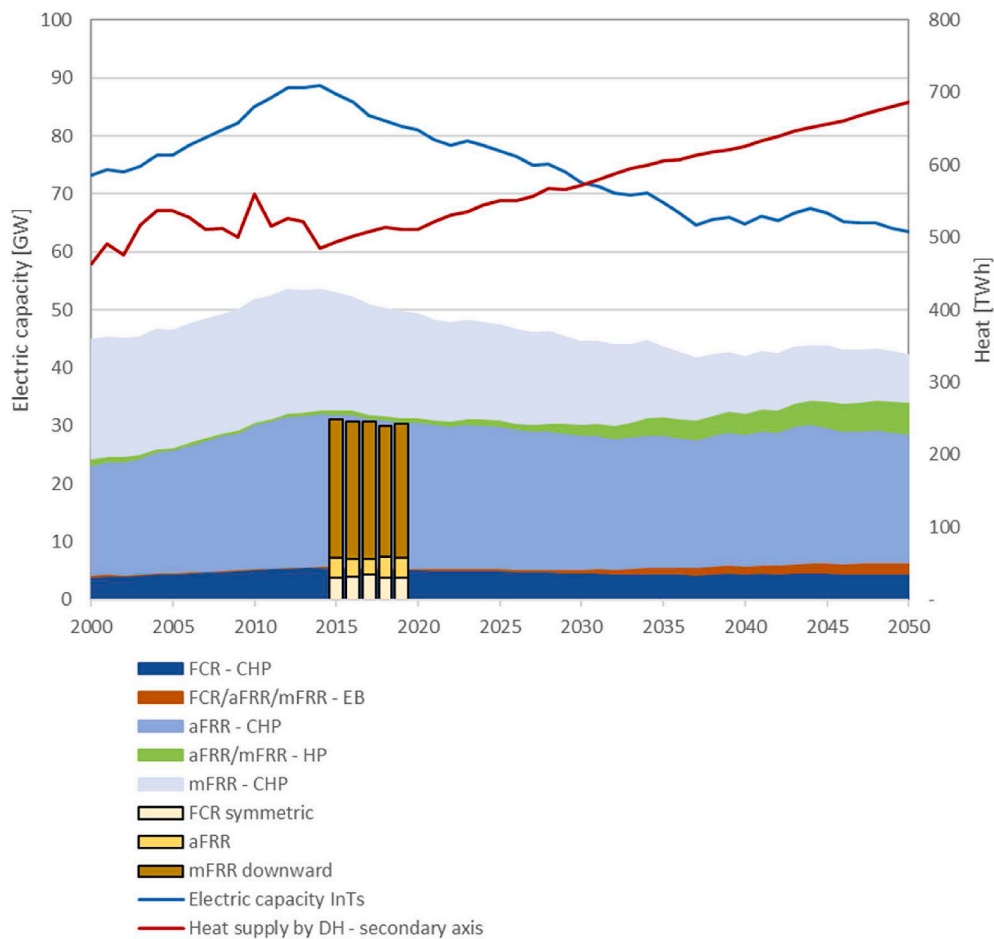
Fig. 11. *Technical potential of DH electric capacity available in the EU25 + UK for FCR, aFRR and mFRR balancing, and* 95th *percentile of the DOWNWARD balancing reserves contracted by EU TSOs, based on POTEnCIA scenario up to 2050. The potential for aFRR includes the one for FCR and the mFRR potential the previous two (mFFR ⊂ aFFR ⊂ FFR) based on the ramping period constraints.*

References

[1] IRENA. Energy transition n.d. https://www.irena.org/energytransition#:~:text=The-energy-transition-is-a,emissions-to-limit-climate-change. [Accessed 20 January 2020].

[2] Raux-Defossez P, Wegerer N, Pétillon D, Bialecki A, Bailey AG, Belhomme R. Grid services provided by the interactions of energy sectors in multi-energy systems: three international case studies. Energy Procedia 2018;155:209–27. https://doi.org/10.1016/j.egypro.2018.11.055.

[3] Pavičević M, Mangipinto A, Nijs W, Lombardi F, Kavvadias K, Jiménez-Navarro JP, et al. The potential of sector coupling in future European energy systems : soft linking between the Dispa-SET and JRC-EU-TIMES models. Appl Energy 2020;267:115100. https://doi.org/10.1016/j.apenergy.2020.115100.

[4] Heggarty T, Bourmaud JY, Girard R, Kariniotakis G. Multi-temporal assessment of power system flexibility requirement. Appl Energy 2019;238:1327–36. https://doi.org/10.1016/j.apenergy.2019.01.198.

[5] International Energy Agency (IEA). Status of power system transformation 2019 - power system flexibility. 2019.

[6] Cramton P. Electricity market design. Oxf Rev Econ Pol 2017;33:589–612.

[7] van der Veen RAC, Hakvoort RA. The electricity balancing market: exploring the design challenge. Util Pol 2016;43:186–94. https://doi.org/10.1016/j.jup.2016.10.008.

[8] Lucas A, Kotsakis E, Pegios K, Tsolakis A, Koskinas I, Venizelou V, et al. DR, flexibility forecasting and energy market simulation. Delta project. Future tamper-proof Demand rEsponse framework through seLfconfigured, self-opTimized and collAborative virtual distributed energy nodes. Delta project; 2020.

[9] ENTSO-E. Balancing and ancillary services markets n.d. https://www.entsoe.eu/about/market/#balancing-and-ancillary-services-markets. [Accessed 21 January 2020].

[10] ENTSO-E. An overview of the European balancing market in Europe. 2018. p. 1–16.

[11] Borggrefe F, Neuhoff K. Balancing and intraday market design: options for wind integration. SSRN Electron J 2012;1–30. https://doi.org/10.2139/ssrn.1945724.

[12] Mohandes B, Moursi MS El, Hatziargyriou N, Khatib S El. A review of power system flexibility with high penetration of renewables. IEEE Trans Power Syst 2019;34:3140–55. https://doi.org/10.1109/TPWRS.2019.2897727.

[13] Zappa W. Paris-proof power: Exploring the consequences of different decarbonisation strategies in the European electricity sector. Utrecht University; 2020.

[14] ENTSO-E. Imbalance netting n.d. https://www.entsoe.eu/network_codes/eb/imbalance-netting/. [Accessed 26 January 2021].

[15] Holttinen H, Meibom P, Orths A, van Hulle F, Lange B, O'Malley M, et al. Design and operation of power systems with large amounts of wind power. Final report, IEA WIND Task 25, Phase one 2006–2008. 2009.

[16] Kling WL, Söder L, Erlich I, Sørensen P, Power M, Holttinen H, et al. Wind power grid integration: the European experience. 17th power systems computation conference PSCC. 2011.

[17] Hirth L, Ziegenhagen I. Balancing power and variable renewables: three links. Renew Sustain Energy Rev 2015;50:1035–51. https://doi.org/10.1016/j.rser.2015.04.180.

[18] International Atomic Energy Agency. Non-baseload operation in nuclear power plants: load following and frequency control modes of flexible operation. IAEA Nucl Energy Ser; 2018. p. 1–190.

[19] Jomaux J, Mercier T, De Jaeger E. Provision of frequency containment reserves with batteries and power-to-heat. IEEE Manchester PowerTech; 2017. https://doi.org/10.1109/PTC.2017.7980915. 2017.

[20] Sorknæs P, Lund H, Andersen AN, Ritter P. Small-scale combined heat and power as a balancing reserve for wind – the case of participation in the German secondary control reserve. Int J Sustain Energy Plan Manag 2014;4:31–42. https://doi.org/10.5278/ijsepm.2014.4.4.

[21] European Commission. Powering a climate-neutral economy: an EU strategy for energy system integration. 2020.

[22] Ruhnau O, Hirth L, Praktiknjo A. Heating with wind: economics of heat pumps and variable renewables. Energy Econ 2020;92:104967. https://doi.org/10.1016/j.eneco.2020.104967.

[23] Bloess A, Schill WP, Zerrahn A. Power-to-heat for renewable energy integration: a review of technologies, modeling approaches, and flexibility potentials. Appl Energy 2018;212:1611–26. https://doi.org/10.1016/j.apenergy.2017.12.073.

[24] Guelpa E, Verda V. Thermal energy storage in district heating and cooling systems: a review. Appl Energy 2019;252:113474. https://doi.org/10.1016/j.apenergy.2019.113474.

[25] Kontu K, Rinne S, Junnila S. Introducing modern heat pumps to existing district heating systems – global lessons from viable decarbonizing of district heating in Finland. Energy 2019;166:862–70. https://doi.org/10.1016/j.energy.2018.10.077.

[26] Yilmaz HÜ, Keles D, Chiodi A, Hartel R, Mikulić M. Analysis of the power-to-heat potential in the European energy system. Energy Strateg Rev 2018;20:6–19. https://doi.org/10.1016/j.esr.2017.12.009.

[27] European Commission. An EU strategy on heating and cooling. 2016.

[28] European Commission. Eurostat database n.d. https://ec.europa.eu/eurostat/data/database. [Accessed 5 February 2021].

[29] Jimenez-Navarro JP, Kavvadias K, Filippidou F, Pavičević M. Coupling the heating and power sectors: the role of centralised combined heat and power plants and district heat in a European decarbonised power system. Appl Energy 2020;270:115134. https://doi.org/10.1016/j.apenergy.2020.115134.

[30] Tomita K, Ito M, Hayashi Y, Yagi T, Tsukada T. Electricity adjustment by aggregation control of multiple district heating and cooling systems. Energy Procedia 2018;149:317–26. https://doi.org/10.1016/j.egypro.2018.08.195.

[31] DHC+ Technology Platform. Euroheat & Power. District heating and cooling: a vision towards 2020-2030-2050. 2012.

[32] Lauersen B. EuroHeat & power - Denmark 2019. . [Accessed 3 February 2021].

[33] Averfalk H, Ingvarsson P, Persson U, Gong M, Werner S. Large heat pumps in Swedish district heating systems. Renew Sustain Energy Rev 2017;79:1275–84. https://doi.org/10.1016/j.rser.2017.05.135.

[34] Levihn F. CHPs and HPs to balance renewable power production : lessons from the district heating network in Stockholm. Energy 2017. https://doi.org/10.1016/j.energy.2017.01.118.

[35] Lundqvist D. EuroHeat & power - Sweden. 2019.

[36] Hindsbo J. Electric kettle in a green energy system? Hot|Cool Int Mag Dist Heat Cool 2020. https://doi.org/10.1029/eo077i018p00174-03.

[37] Aste N, Buzzetti M, Caputo P. District heating in Lombardy region (Italy): effects of supporting mechanisms. Sustain Cities Soc 2015;14:43–55. https://doi.org/10.1016/j.scs.2014.07.006.

[38] Galindo-Fernández M, Bacquet A, Bensadi S, Morisot P, Oger A. Integrating renewable and waste heat and cold sources into district heating and cooling systems - case studies analysis, replicable key success factors and potential policy implications. Publications Office of the European Union; 2021. https://doi.org/10.2760/111509.

[39] Bacquet A. Integrating renewable and waste heat and cold sources into district heating and cooling systems. Case studies analysis, replicable key success factors and potential policy implications. External study performed by Tilia for the Joint Research Centre; 2021. https://doi.org/10.2760/111509.

[40] Ma Z, Knotzer A, Billanes JD, Jørgensen BN. A literature review of energy flexibility in district heating with a survey of the stakeholders' participation. Renew Sustain Energy Rev 2020;123. https://doi.org/10.1016/j.rser.2020.109750.

[41] Vandermeulen A, van der Heijde B, Helsen L. Controlling district heating and cooling networks to unlock flexibility: a review. Energy 2018;151:103–15. https://doi.org/10.1016/j.energy.2018.03.034.

[42] Wang J, You S, Zong Y, Cai H, Træholt C, Dong ZY. Investigation of real-time flexibility of combined heat and power plants in district heating applications. Appl Energy 2019;237:196–209. https://doi.org/10.1016/j.apenergy.2019.01.017.

[43] Haakana J, Tikka V, Lassila J, Partanen J. Methodology to analyze combined heat and power plant operation considering electricity reserve market opportunities. Energy 2017;127:408–18. https://doi.org/10.1016/j.energy.2017.03.134.

[44] Zhou Y, Hu W, Mi Y, Dai Y. Integrated power and heat dispatch considering available reserve of combined heat and power units. IEEE Trans Sustain Energy 2019;10:1300–10.

[45] Turk A, Wu Q, Zhang M, Østergaard J. Day-ahead stochastic scheduling of integrated multi-energy system for flexibility synergy and uncertainty balancing. Energy 2020;196:117130. https://doi.org/10.1016/j.energy.2020.117130.

[46] Kumbartzky N, Schacht M, Schulz K, Werners B. Optimal operation of a CHP plant participating in the German electricity balancing and day-ahead spot market. Eur J Oper Res 2017;261:390–404. https://doi.org/10.1016/j.ejor.2017.02.006.

[47] Tan J, Wu Q, Hu Q, Wei W, Liu F. Adaptive robust energy and reserve co-optimization of integrated electricity and heating system considering wind uncertainty. Appl Energy 2020;260:114230. https://doi.org/10.1016/j.apenergy.2019.114230.

[48] Terreros O, Spreitzhofer J, Basciotti D, Schmidt RR, Esterl T, Pober M, et al. Electricity market options for heat pumps in rural district heating networks in Austria. Energy 2020;196. https://doi.org/10.1016/j.energy.2019.116875.

[49] Blanco I, Guericke D, Andersen AN, Madsen H. Operational planning and bidding for district heating systems with uncertain renewable energy production. Energies 2018;11. https://doi.org/10.3390/en11123310.

[50] Meesenburg W, Ommen T, Elmegaard B. Dynamic exergoeconomic analysis of a heat pump system used for ancillary services in an integrated energy system. Energy 2018;152:154–65. https://doi.org/10.1016/j.energy.2018.03.093.

[51] European Commission. METIS technical note T4: overview of European electricity markets. 2016.

[52] ENTSO-E. All TSOs' proposal for the implementation framework for the exchange of balancing energy from frequency restoration reserves with automatic activation in accordance with Article 21 of Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing. ENTSO-E; 2018.

[53] ENTSO-E. All TSOs' proposal for the implementation framework for the exchange of balancing energy from frequency restoration reserves with manual activation in accordance with Article 21 of Commission Regulation (EU) 2017/2195 establishing a guideline on electricity balancing. ENTSO-E; 2018.

[54] International Energy Agency. Energy technology perspective. IEA; 2014.

[55] Iov F, Khatibi M, Bendtsen JD. On the participation of power-to-heat assets in frequency regulation markets-a Danish case study. Energies 2020;13. https://doi.org/10.3390/en13184608.

[56] ENTSO-E. Volumes of contracted balancing reserves n.d. https://transparency.entsoe.eu/balancing/r2/balancingVolumesReservation/show. [Accessed 15 December 2020].

[57] Kanellopoulos K, Kavvadias K, Careri F, De Felice M, Busch S, González I. The operation of the European power system in. 2016. 2019. https://doi.org/10.2760/434010.

[58] European Commission. Achieving the 10% electricity interconnection target - making Europe's electricity grid fit. for 2020;2015:1–16.

[59] Kondziella H, Bruckner T. Flexibility requirements of renewable energy based electricity systems - a review of research results and methodologies. Renew Sustain Energy Rev 2016;53:10–22. https://doi.org/10.1016/j.rser.2015.07.199.

[60] European Commission. The POTEnCIA central scenario: an EU energy outlook to 2050. 2019. https://doi.org/10.2760/78212.

[61] Paardekooper S, Lund RS, Mathiesen BV, Chang M, Petersen UR, Grundahl L, et al. Heat Roadmap Europe quantifying the impact of low-carbon heating and cooling roadmaps. 2018.

[62] Jiménez Navarro JP, Kavvadias KC, Quoilin S, Zucker A. The joint effect of centralised cogeneration plants and thermal storage on the efficiency and cost of the power system. Energy 2018;149. https://doi.org/10.1016/j.energy.2018.02.025.

[63] Pezzutto S, Zambotti S, Croce S, Zambelli P, Garegnani G, Scaramuzzino C, et al. Hotmaps project, D2.3 WP2 report – open data set for the EU28. 2018. www.hotmaps-project.eu.

[64] Lund H. Renewable heating strategies and their consequences for storage and grid infrastructures comparing a smart grid to a smart energy systems approach. Energy 2018;151:94–102. https://doi.org/10.1016/j.energy.2018.03.010.

[65] Hedegaard K, Mathiesen BV, Lund H, Heiselberg P. Wind power integration using individual heat pumps - analysis of different heat storage options. Energy 2012;47:284–93. https://doi.org/10.1016/j.energy.2012.09.030.

[66] Hennessy J, Li H, Wallin F, Thorin E. Flexibility in thermal grids: a review of short-term storage in district heating distribution networks. Energy Procedia 2019;158:2430–4. https://doi.org/10.1016/j.egypro.2019.01.302.

[67] Werner S. International review of district heating and cooling. Energy 2017;137:617–31. https://doi.org/10.1016/j.energy.2017.04.045.

[68] Salpakari J, Mikkola J, Lund PD. Improved flexibility with large-scale variable renewable power in cities through optimal demand side management and power-to-heat conversion. Energy Convers Manag 2016;126:649–61. https://doi.org/10.1016/j.enconman.2016.08.041.

[69] Mikkola J, Lund PD. Modeling flexibility and optimal use of existing power plants with large-scale variable renewable power schemes. Energy 2016;112:364–75. https://doi.org/10.1016/j.energy.2016.06.082.

[70] Radu A, Eremia M, Toma L. Participation of the electric vehicles in the balancing market. Electr Veh Int Conf 2019:1–6.

[71] Williams S, Short M, Crosbie T. On the use of thermal inertia in building stock to leverage decentralised demand side frequency regulation services. Appl Therm Eng 2018;133:97–106. https://doi.org/10.1016/j.applthermaleng.2018.01.035.

[72] European Commission. Directive of the European Parliament and of the Council Amending Directive (EU) 2018/2001 of the European Parliament regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/65. 2021.

[73] Buffa S, Cozzini M, D'Antoni M, Baratieri M, Fedrizzi R. 5th generation district heating and cooling systems: a review of existing cases in Europe. Renew Sustain Energy Rev 2019;104:504–22. https://doi.org/10.1016/J.RSER.2018.12.059.

[74] IRENA. Renewable. Energy prospects for the Russian federation (REmap working paper). 2017.

[75] ENTSO-E. Monthly statistics reports n.d. https://www.entsoe.eu/publications/statistics-and-data/#monthly-statistics-reports. [Accessed 15 February 2021].