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Improve the flexibility provided by combined heat and power plants (CHPs) – a review of potential technologies

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ABSTRACT

The rapid growth of intermittent renewable energy for electricity production brings a huge challenge to keep the balance between supply and demand in power systems, which further raises the need of flexibility. It has been well recognized that combined heat and power plants (CHPs) can play an important role in the provision of flexibility, due to their ability to switch the production between electricity and heat. However, there still lacks a comprehensive review about the flexibility provided by individual technologies involved in CHPs, which hinders the exploration of the capability of CHPs. In addition, new technologies and technology couplings have been proposed and adopted to further improve the flexibility in CHPs. This review aims to characterize the flexibility features of technologies that have been adopted or can be adopted by CHPs. Ramp rate, operation range, and power capacity are selected as key performance indicators for assessing technologies for providing flexibility services. Based on the collected result, suggestions are provided regarding the selection of technologies to enhance the flexibility provided by CHPs.

1. Introduction

Due to the rapid growth of variable renewable energy (VRE), especially wind and PV power, and the decommissioning of nuclear power, keeping the balance between electricity production and consumption in the grid becomes more challenging. Flexibility is the ability of a power system to respond to changes in demand and supply. In order to accommodate more VRE to fully achieve the climate goal, improving the flexibility of the power system is of great significance [1].

Exploring the sources of flexibility has attracted tremendous attention [2–5]. Akrami et al. divided the power system flexibility into two categories: physical and structural flexibilities [6]. In general, the physical measures include flexible operation of technical processes such as, power plants, demand side management, reinforcement of distribution and transmission facilities, and integration of energy storage systems; while the structural flexibility is the capability to exploit physical flexibility through operational instructions or market procedures [6],[7].

Thermal power plants are playing a key role in the physical flexibility due to their large share in the electricity generation [8–11]. Unfortunately, the flexibility that can be provided by conventional thermal power plants based on Rankine cycle is limited [10]. Even though steam turbines (STs) can respond quickly and with a large operation range, their ability is usually limited by the boiler, because excessively fast adjustment in a wide range can potentially threaten the operational reliability of the boiler [12]. Co-generation power systems can offer a higher flexibility, for example the combined heat and power plants (CHPs), which can switch the production between electricity and heat. It has been well recognized that CHPs can respond rapidly to market signals, provide flexibility services, improve the electricity system resilience and reduce network losses, bottlenecks and costs [13].

Even though many works have been conducted to explore the flexibility provided by CHPs, there have not been many review papers that systematically summarize the technologies that CHPs can adopt to improve the flexibility. De Souza et al. reviewed the role of CHPs with penetration of VRE, which covers the product flexibility in CHPs [14]. Wang et al. have reviewed the physical flexibility and the characteristics of different CHP technologies [15], with focuses on the overall performance and operational profits. The flexibility applications of CHPs were also discussed in the integrated energy scenarios from the perspectives of demand side, plant and system owners. It has been concluded that variability and uncertainty from VRE require the CHP to have faster ramp rate, lower minimum loads, shorter start-up time and overload capability, which is in consistency with the findings of Beiron et al [16]. However, attention was mainly paid to the flexibility provided by CHPs as a whole and the optimization of their operation strategies. There are few details about the flexibility provided by individual technologies involved in CHPs. More importantly, the analysis didn't consider the re-

HOB, Heat only boilers.

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Nomenclature

aFRR	Automatic Frequency Restoration Reserve
CCGT	Combined cycle gas turbine
CHP	Combined heat and power plants
DA	Day ahead market
DH	District heating
DSO	Distribution System Operators
FCR	Frequency containment reserve
FC	Fuel Cell
GT	Gas turbine
HP	Heat pump
ID	Intraday market
IGCC	Integrated gasification combined cycle
KPIs	Key performance indicators
LHV	Lower heating value
MES	Multi-Energy systems
mFRR	Manual Frequency Restoration Reserve
P2H	Power to heat
PEM	Polymer electrolyte membrane
PV	Photovoltaic
RR	Replacement reserve
ST	Steam turbine
TES	Thermal energy storage
TSO	Transmission System Operators
VPP	Virtual Power Plant
VRE	Variable renewable energy

quirement of the flexibility services; and how to select technologies regarding the flexibility services was not discussed. Witkowski et al. reviewed the role of thermal technologies including CHPs in multi-energy systems (MESs) [17]. They reported that the capabilities of MESs to provide flexibility through the integration in CHPs are mainly dependent on technical flexibility features such as power output, ramp rate and hot/cold start time.

Today, the flexibility provided by CHPs is limited. One important reason is the unattractive benefit, which is resulted from two aspects: unfavorable market conditions and limited physical flexibility that can be provided. CHPs usually participate in the day-ahead market (DA) and intraday market (ID). Some works have verified that providing the ancillary services, such as frequency regulation, can potentially increase the profit of CHPs compared to participating in DA and ID markets [18] [19],[20]; whereas, the increase was not significant [12], which was owing to the low electricity prices and limited flexibility. However, it has also been confirmed that improving the operational flexibility of CHPs is vital to ensure their economy of operation in different electricity markets [21]. Therefore, in order to further promote the flexibility provided by CHPs, there is an urgent need to understand how to retrofit the existing CHPs to enhance their capability of providing flexibility. This work reviews the technologies commonly adopted in CHPs and the potential technologies that can be used for CHP retrofitting. The objective is to characterize the flexibility features of each technology and provide a guideline to the decision makers regarding the selection of technologies under different circumstances.

The rest of the paper is organized as follows: Section 2 summarizes the identified flexibility services which can increase the share of VRE and the selected key performance indicators (KPIs) for flexibility; Section 3 describes the flexibility characters of the technologies adopted by CHPs; Section 4 presents the new technologies that can be integrated in CHPs to improve the flexibility; and Section 5 and 6 discuss the existing knowledge gaps and conclude the major findings respectively.

2. About flexibility

2.1. Flexibility services

EU Horizon project MAGNITUDE has identified the most important flexibility services to be provided by MESs, which can increase the share of VRE, avoid curtailment of VRE, and enhance the security of supply [22]. In the meantime, needs of the system operators, namely the Transmission System Operators (TSOs) and Distribution System Operators (DSOs), the States/policy makers and energy sellers and buyers to trade energy were taken into account [23]. For CHPs, as power generator or energy seller, the most relevant flexibility services include: Frequency containment reserve (FCR), Automatic Frequency Restoration Reserve (aFRR), Manual Frequency Restoration Reserve (mFRR), Replacement Reserve (RR), DA market, and ID market, which will be the focus of this work.

ID and DA markets are common to provide flexibility in liberalized economies. In the DA market, power plants have to submit offers to with their respective minimum selling price [24] [24]. In parallel, retailers submit their price bids for buying. The market operators use market clearing procedure to clear the DA market. Typically, the DA market clears one day ahead and on an hourly basis [25]. The ID market is either based on continuous trading mechanisms or on auctions [26]. Although the energy balance is usually secured in the DA market; but sometimes, there are disturbances, which can cause an imbalance between the closing time of the DA market and the delivery. To settle the market balance, producers and consumers can trade energy volumes closer to the time of delivery in the ID market. For example, in Sweden, the available capacity to the ID market is publishes at 14:00 Central Europe Time and traded on an hourly basis. Continuous prices are set and bids with the best prices are prioritized [27].

Power grids attempt to balance electricity production with consumption all the time. CHPs can also act as reserves by either increasing or decreasing their electric power as per the requirement of the power system. Frequency of the electricity grid indicates the balance between production and consumption, but deviations occur continuously. To balance these deviations, electric grids usually procure various kinds of reserves from balancing markets. FCR/aFRr/mFRR/RR are the services in balancing markets for short-term flexibility [28]. Balancing markets are present to maintain or balance the real-time differences between generation and demand that may arise due to equipment failures, unpredicted consumptions or uncertainties of VRE. Such markets have to restore the required operating level with activation time in seconds to minutes [24]. The balancing markets are very different in various countries.

For different services, the technical requirements are also different; and requirements for the same service can also be different in different countries. As an example, Table 1 lists some of the technical requirements by DA, ID, and balancing markets implemented in Scandinavian region.

2.2. Flexibility KPIs

The capability of providing flexibility services depends on the operating characteristics of technologies. In this work, the following KPIs are used to characterize the flexibility provided by a technology [2],[31].

- Ramp rate is usually measured in power over time, which shows how quickly the power production/consumption can be modified (up/down) to meet the variation of demand.
- Operation range, which shows the possible range of power production/consumption. It is beneficial for a technology to have a wider operation range to avoid shutdown. However, part-loads can decrease the efficiency of the technology and increase the maintenance requirement [32].
- Start-up time shows the time required by a system which operation changes from zero to full load. For flexibility, a short start-up time

Table 1
Requirements for different flexibility services [29] [30],.

	DA	ID	FCR	aFRR	mFRR
Operational day	[00:00–24:00]	–	[00:00–24:00]	[00:00–24:00]	[00:00–24:00]
Up/Down Regulation	Unidirectional	Unidirectional	Separate asymmetrical bids	Symmetrical bid	Separate asymmetrical bids
Minimum bid	0.1 MW	0.1 MW	0.1 MW	5 MW	10 MW
TSO Signal Exchange Rate	n/a	n/a	n/a	4–10 s	4–10 s
Estimation of reserve	n/a	n/a	Not required	yes	no
Measurement Accuracy	n/a	n/a	<10 mHz.	<10 mHz.	<10 mHz.
Activation response	According to schedule	According to schedule	First 50% in 15s and rest in max 30 s	85% full activation in max 15 min	85% full activation in max 15 min
Response delay	n/a	n/a	n/a	max 135 s	max 135 s
Duration	1 h	15 min – 1 h	At least 15 min	1 h	1 h

n/a: not applicable.

Table 2
CHP power plants technological factsheet [34]–[38].

	Small scale GT based CHPs (Standalone)	CCGT based CHPs	Coal CHPs	Biomass CHPs	Gas engine based CHP	Gas boiler-based CHPs
Electrical efficiency, %	30–36	42–47	24–28	16–36	30–42	26–32
Thermal efficiency, %	50–44	38–33	62–64	40–85	44–50	40–85
Lifetime, yr	25	25	40	25	20	25
Operation range, %	70–80	75–85	75–85	76–91	50–60	75–80
Power capacity, MWe	5–25	12–300	15–200	50	0.07–6	0.3–10

is desirable to react faster. However, fast start-up can increase the thermal stress to the equipment that can result in a shorter lifetime [24].

3. Flexibility provided by conventional CHPs

There are different configurations for CHPs, depending on the type of fuel and how fuel is converted. This section mainly focuses on the conventional CHPs based on combustion.

3.1. Configurations of CHPs

The most common configuration of CHPs is based on combustion in boilers. Solid, liquid or gas fuel can be combusted in the boiler in the presence of excess air, and chemical energy is converted to heat, which is used to generate steam for the coupled Rankine cycle. In order to provide heat to the district heating (DH), steam can be extracted from the steam turbine at different pressures and condensed to release heat. In general, there are two types of STs: back pressure ST and condensing ST (See Section 3.2.2 for more details). Moreover, waste heat can also be recovered from flue gas condensation to provide additional heat [33].

For large scale gas turbines (GTs), the configuration is normally based a combined cycle (CCGT). In the topping Brayton cycle, the gas fuel is burnt in the presence of compressed air in the combustor and the flue gas expands in the turbine to produce electricity. Then, the exhaust gas is used to drive a bottoming Rankine cycle. Similar to the boiler-based CHPs, the condensation of steam supplies the heat demand. For small scales GTs and engines, there is normally no bottoming cycle. After expansion to produce electricity in engines or turbines, the exhaust gas is cooled down and heat is recovered.

Table 2 summarizes the important features of various configurations of conventional CHPs. The clear differences in the technical specifications imply that the capability of providing flexibility services will be different.

3.2. Flexibility in individual technologies

As illustrated in Section 3.1, the common technologies involved in CHPs include boilers, engines, gas turbines and STs. The following section will review the flexibility provided by each technology by using the KPIs defined in Section 2.2.

3.2.1. Boilers

There are different types of boilers differentiated by the capacity, fuel type, design, quality of produced steam etc.

Gas boilers have a limited ability to provide capacity and flexibility products when they are online. Start-up times generally are too great to provide intra-hour flexibility. The typical start-up time for gas-fired steam boilers is between 4 and 6 hours. There are also gas boilers (HOBs) that are not producing steams and provide only heat to DH. The typical start-up time for HOBs is usually 1–2 hours [38].

Biomass is commonly used as fuel for CHPs. Fixed bed and fluidized bed boilers are normally used for combusting biomass. Fixed bed boilers, also known as stoker boilers, combust solid fuel in the presence of excess air. It mainly consists of four components: fuel feeding system, a moving or stationary grate for the combustion of fuel which also provides a pathway to let air required for combustion enter, an overfired system for excess air, and an ash disposal system [33],[35–39]. Typically, fixed bed boilers have an operation range of 40%-90% of the full load and show a high level of fuel flexibility [39]. Compared with fixed bed boilers, fluidized bed boilers are more compact and can achieve higher efficiency, lower emissions and even higher fuel flexibility [33],[40]. In fluidized bed boilers, solid fuel is combusted in the presence of inert or incombustible bed. Air is entered from the bottom to keep the bed of inert material in a fluidized state. Fluidized bed boilers can be further divided into: bubbling fluidized bed boilers and circulating fluidized bed boilers [39],[40]. As the properties of biomass vary significantly and are affected by many factors, such as moisture content, fuel composition etc., little quantitative information is available about the ramp rate of biomass boilers. Referring to coal fired boilers, the ramp rate can be 1.5 – 6 % of the nominal load per minute. Table 3 displays the main parameters for different types of boilers.

3.2.2. Steam turbines (STs)

A steam turbine converts thermal energy of pressurized steam to mechanical work on a rotating output shaft through expansion. STs are manufactured in a variety of sizes, for example, utility STs ranging from 90 MWe to 1900 MWe with inlet steam pressure of 80 - 260 bar and steam temperature of 310 °C – 610 °C [41]. For CHPs, it is normally less than 250 MWe [42–44].

Two types of STs are commonly used in CHPs: condensing STs, and backpressure STs [45]. For condensing STs, steam exits the turbine at a pressure lower than atmospheric pressure and the external cooling source is needed, which can lead to a higher capital cost [46]. To pro-

Table 3
Technology Factsheet and flexibility parameters of boilers commonly used in CHPs [33].

	Fixed bed boilers	Fluidized bed boilers	Co-firing with pulverized coal boilers	Co-firing – fixed bed or fluidized bed coal boilers	Gas boilers
Fuel type	Sawdust, chips, bark, hog fuel, sander dust, shavings	Wood residue, peat, saw dust, chips	Sawdust, bark, shavings, sander dust	Sawdust, bark, shavings, sander dust	Mainly natural gas
Power capacity, MW	4–300	Up to 300	Up to 1000	Up to 300	Up to 300
Operation range, %	40–90	40–90	40–90	40–90	16–100
Ramp rate (%power/min)	3–6	3–6	2–6	2–6	4–6

Table 4
Technology Factsheet and flexibility parameters of steam turbines [42],[49]–[54].

Parameter	Single stage Condensing STs	Backpressure STs	Multistage Condensing STs	Backpressure STs
Power capacity, MWe	0.1–6	0.1–6	5- 500	5–250
Turbine inlet T, °C	150–500	150–500	300–620	300–565
Turbine exit T, °C	50–70	100–400	50–70	100–400
Net Electrical Efficiency, % of LHV	10–20	3–15	15–47	3–25
Operation range, % of Load	max 100*	max 100*	25/50–100	25/50–100
Ramp rate, % of power/ min	1.5–4%	1–2%	1–8%	

*The lower boundary is not available

Table 5
Flexibility parameters of boilers + steam turbines depending on the fuel [42],[49–54].

Fuel	Ramp rate [% nom. power/min]	Operation range [%]	Commonly used minimum load [%]
Hard coal	1–6	25	40
Lignite	1–4	35	50
Gas	up to 8	30	40
Oil	up to 8	30	30
Nuclear	1–2	50	50
Biomass	Up to 6	35	50

vide the heat needed by DH, steam can be extracted from intermediate stages and condensed. Backpressure STs are designed to have a higher outlet steam pressure than condensing STs. As the condensation temperature is determined by the condensation pressure, the condensation of the exhausted steam from backpressure STs can release heat at a temperature satisfying the need of DH. Usually, condensing STs have higher capacities than backpressure STs [45] and are more flexible. The operation of backpressure STs is primarily dependent on the heat demand. When there is not enough heat load, which implies there is no guarantee of steam condensation, the load of steam turbines needs to be reduced. The cold start-up time of STs is in the range of 5 - 10 hours and the hot start-up time is in the range of 2.5 - 6 hours [47],[48].

The flexibility in STs is limited by their cycling capabilities and on/off frequency that are the main source of progressive deterioration of turbines material. Therefore, STs require scheduled monitoring and testing in order to operate flexibly for longer run [46]. To minimize the need for on/off operations, STs can run continuously considering the minimum allowed load. Table 4 shows the technology factsheet and flexibility parameters of STs most commonly used in CHPs.

STs are commonly coupled with boilers; hence, it is more important to understand the flexibility of the combination of boilers and STs. The flexibility parameters of the combination of boilers and STs are presented Table 5. The overall systems are expected to be more resistant to load change cycles and be able to provide ramp rates at a level from 10%/10 s to 10%/min [52].

Operating STs in bypass mode is another technical solution to provide the physical flexibility. The bypassed steam does not produce power and only generates heat. The variation of bypassed steam is governed by the ramp rate of STs.

3.2.3. Gas turbines

A gas turbine (GT) usually consists of a combustion chamber, a compressor (axial or centrifugal flow) and a generator. GTs vary in capacity from 30 kW (micro turbines) to several hundred MW. Table 6 describes the technology factsheet and flexibility parameters of most used GTs in CHPs .

GTs require 55 minutes (hot start) to 170 minutes (cold start) to start and 20 to 25 minutes to stop [44]. Additionally, a minimum of 64 hours is required between two cold starts, while 16 hours between warm starts and even less between hot starts [57]. Ongoing research and development aim at improving the efficiency and flexibility, which can reach 65% of fuel lower heating value (LHV) and a ramp up rate of 7.5%/min [58].

3.2.4. Gas engines

Reciprocating engines normally consist of pistons and cylinders where fuel is combusted. This piston is connected to a crank shaft, which drives an alternator to generate electricity. Gas engine sizes range from 10 kW_e to 20 MW_e [59],[60] and the thermal efficiency, electrical efficiency, and total efficiency are respectively about 43 %, 46 – 48 % and 89 % of LHV of the fuel [60]. Gas engines have a high operational availability [60] and short start-up time (5 - 10 minutes), which make them responsive to variable demand. The full load can be achieved in less than 10 minutes . However, they have minimum load requirements of 30 – 35 % [61]. Regular maintenance is required for gas engines because of the need for lubricant oil change [62] [63].

In addition, gas engines may be aggregated to provide high flexibility. When there is a need to decrease the power load, some engines can be shut down and the others may still run at full load, maintaining high

Table 6
Technology Factsheet and flexibility parameters of gas turbines [44] [51–53].

Parameter	Simple cycle combustion heavy & duty turbine	Simple cycle Aero-derivative	Combined cycle
Power Capacity, MWe	3–593	36–117	44–593
Turbine outlet Temperature , °C	365–465	430–530	Hot water or steam depending on the pressure
Net Electric Efficiency, % of LHV	23–40	32–42	52–62
Thermal Efficiency, % of LHV	44–50	44–50	33–38
Operation range, % of Load	25/40–100	5–100	30/60–100
Ramp rate, % of power/min	7.5–16.3	82–132	5.2–6

Table 7
Technology Factsheet and flexibility parameters of gas engines [55],[56],[59].

Parameter	Value
Power Capacity, MW_e	0.1–20
Net Electrical Efficiency, % of LHV	29.6–42
Thermal Efficiency, % of LHV	35–53
Operation range, % of load	30–100%
Ramp rate, % of power/min	20–50 (100 for already started engines)

efficiency of the system [55]. Gas engines can operate more efficiently at partial loads. A very high ramp rate may be problematic, especially for large engines that are connected to high voltage grid due to the risk of overheating of transformer during cold start up [56].

Table 7 displays the technology fact sheet for gas engines.

Gas engines are a mature technology; however, there is still need for further development to increase the achievable power output and efficiency (electric efficiency up to 53% of LHV).

3.2.5. Thermal energy storage (TES)

TES systems can store heat that can be used later at different temperatures, places, or capacities as per demand through discharging. The main purpose of TES is to solve the mismatch between energy generation and energy use. Implementing TES is an effective way to increase the flexibility of energy systems.

TES — from a physical perspective — can be classified into sensible, latent (also called as phase change material (PCM) storage) and thermochemical heat storage. However, the sensible TES is the most widely used in CHPs due to its low cost. The stored energy is proportional to the temperature change of the used materials. Today, liquids (mostly water), molten salts and solids are commonly heat storage media. Solid materials can be utilized in a wide temperature range and heated up to very high temperature (e.g. refractory bricks in Cowper regenerators to 1000 °C) [64].

Flexibility parameters and technology parameters of different types of TES are presented in Table 8.

TES provides an opportunity to decouple the heat and electricity production in CHPs. For example, for condensing STs, when the electricity demand is low, more steam can be extracted and heat can be stored in TES; when the electricity demand is high, TES can be discharged to cover the heat demand and more electricity can be produced. For backpressure STs, when the electricity demand is low while the heat demand is high, TES can be discharged to provide heat, which enables the ramp down of the power generation; when the electricity demand is high while the heat demand is low, TES can be charged to absorb heat, which enables the ramp up of the power generation. Ritcher et al [66] stated that plant

Table 8
Technology Factsheet and flexibility parameters of TES [65].

	Sensible heat TES
Storage medium	Water
Storage duration	Minutes to days
Response time[1]	Seconds to minutes
Power capacity[2]	0–5 MW
Operation range	0–100 % load
Discharge time	1–8 h
Self-discharge/day[3]	0.5%
Energy density (Wh/kg)[4]	80–120
Lifetime (yrs)	10–20

[1] Response time is the speed at which energy is absorbed on TES or released from it.
[2] Power capacity is the maximum power, which can be delivered by the TES during discharging.
[3] Self-discharge is the dissipation of unused energy initially stored.
[4] Energy density is the amount of energy stored in each system per unit mass.

load can be adjusted in a significant manner through the integration of TES with CHPs. It has been shown that TES can enhance the ramp rate of a plant to five times of its original value (18 MW/min) [67]. According to Wojcik et al., coupling of TES with steam cycles can also increase its overload capacity by 5%–10% and reduce its minimum load by a 5%–15% [64]. Wang et al. [68] found that there is a better coordination between the boiler and turbine through the coupling of TES with CHPs and it improves the ramp rate and load following capability. Rinne et al. [69] analyzed the flexibility potential of CHPs in Finland through the integration of TES. They found that coupling of TES with CHPs increases their ramping capability; however, the capacity of TES must be at 30% or above of the heat demand to achieve the realistic ramp rates [69]. Zhou et al. [70] did dynamic simulations for a TES integrated steam cycle and reported that the coupling increases the ramp rate to 6.19%.

3.3. Flexibility services provided by CHPs

Varying the power to heat ratio of CHPs is one of the straightforward methods to provide the physical flexibility. However, heat is considered as the core business of CHPs. Strictly meeting the heat demand limits the flexibility provided by the conventional CHPs as the electricity production is planned based on the heat generation. CHPs mainly participate in ID and DA markets and providing flexibility in the regulating power market is less often. To motivate CHPs to provide more flexibility, additional revenues in other electricity markets rather than the DA and ID, are also needed, which requires lower minimum loads, higher ramp rates and lower start-up duration with lower start-up costs.

Much research focused on using TES to enhance the flexibility provided by CHPs. There are studies about the participation of CHPs in one or several of DA, ID and balancing markets [29],[71],[66–72]. Kum-

Table 9
Flexibility services provide by CHPs.

Ref	Flexibility services	Implemented technologies	Flexibility performance	Main findings	Note
[72]	Automatic Frequency Restoration Reserve (aFRR)	CHP	Case 1: 20% capacity is reserved. The power levels started to change within 15 seconds and the desired power levels were reached in less than 3 minutes Case 2: manipulating heat power output of the DH accumulator. the power levels started to respond within 30–40 seconds after the set point changes and the desired power levels were reached within 2–3.5 minutes	For case 1, the dynamic bottle neck can be in the dynamics of boiler; while for case 2, there were significant fluctuations in live steam pressure that were caused by the rather slow dynamics of the coal boiler. One reason for the slow response is the sluggish response of coal mills, which might have time delays of several minutes without the excessive overloading of mill air feed	Little info was provided regarding modeling. No constraint about ramp rate was given.
[77]	DA + ID	CHP+TES	–	Profits can further increase if the CHP can bid on two markets (+6.5% compared to the one market situation).	No constraint about ramp rate was included
[75]	DA + balancing market	CHP+an auxiliary boiler + TES	The Belgian TSO provides actualized information on the current imbalance volume every 3 min	The ‘flexible real time’ adjusts the CHP output every time step depending on the actual imbalance price and RES-based generation	No constraint about ramp rate was included
[78]	DA + minute reserve power	CHP based on condensing STs + TES	15 min delivery time	It was found that shutdown of the CHP could be more beneficial than operating the CHP for participation in the energy balancing market in some scenarios	It was only assumed the startup time is 15mins. No detailed price was given.
[73]	DA+ balancing market (Minute reserve)	Gas-fired CHP+TES	15 minutes delivery time and the minimum bid size is 5 MW	Trading in the considered electricity markets can lead to a significant decrease of expected net acquisition costs. Additional revenues gained from trading offset higher generation costs caused by a market price-oriented operation of the CHP	No constraint about ramp rate was included
[18]	DA, ID + frequency containment balancing markets (FCR-N and FCR-D)	CHP	2MW of capacity was reserved	it is worthwhile to participate in the balancing market, yet at the expense of the DA markets, balancing market participation may cause fluctuations in the heat delivery, and even minor shortages in heat delivery may occur if the electrical power has to be up regulated for a long time	No constraint about ramp rate was included
[71]	DA and aFRR	backpressure and condensing steam cycle modes + TES	For transitions between backpressure and condensing steam cycle modes, an assumed minimum stay-time of a) 1 h; or b) 10 h is required before another transition is allowed.	Low-price periods favor increased heat generation and frequency response delivery	No constraint about ramp rate was included

bartzky et al. [73] briefly summarized the literature on the operation and trading procedures of CHPs in different electricity markets. Most of studies focus on the DA market. Both linear and non-linear optimization algorithms have been proposed to optimize profits derived from trading power in a spot market. Meanwhile, it was found that the CHP with thermal storage was one of the most commonly studied configurations as thermal storage enables the plant to decouple the heat generation from the heat demand. Nuytten et al., [74] have analyzed the maximal flexibility potential of a small-scale CHP coupled with centralized and decentralized thermal storage. The results indicated that the central thermal energy storage enables much greater flexibility.

In addition to DA, CHPs can provide other flexibility services, which are summarized in Table 9. Korpela et al. [72] analyzed the dynamic operability of a CHP for providing aFRR. it was concluded that CHP production can contribute to balancing the power grid. The increase of flexibility comes from two ways that are either relatively small amounts of power that can be obtained fast or significant amount of power that can be obtained slowly. The results indicate that both cases fulfill the requirements and the DH network operation is affected only slightly. However, the rapid power level changes are disturbances to CHP boilers and DH networks that the process components and automation systems must adapt to. Therefore, these aspects must be considered carefully when applying such new operation practices in existing CHPs [75],[76].

Ridder and Claessens [77] proposed an optimal bidding strategy for an industrial CHP selling their power on day-ahead and intraday markets. The method probability density functions were used to determine the future time evolution of both heat demand and market prices. By exemplified for the Belgian market, combining both markets can increase the expected profits significantly.

Riveros et al. [75] proposed a methodology to evaluate the optimal bidding strategy of a virtual power plant (VPP) composed of a CHP–DH and VRE based generators, which considered three bidding strategies:

Table 10
Technology Factsheet and flexibility parameters of HP [17].

Parameter	Value
Power Capacity, MWe	0.002–7.5
T of heat source, °C	-20 - +50
T of delivered heat, °C	30–100
Operation range, % of load	10–100
Ramp rate, % of power/min	20

'static', 'flexible day ahead' and 'flexible real time'. The 'flexible real time' case was performed using a rolling-horizon approach to consider the imbalance prices, which can lead to more profit than the other two.

Schulz et al. [78] developed a model to support energy companies planning their bids for the energy balancing market, which can determine the optimal bidding amount based on a forecasted market clearing price. Two approaches, which reflect the risk attitude of the decision maker, were tested, including an expected value approach and a minimax-regret approach are compared. They can lead to different results for the optimization of the available reserve capacity and the operation of the CHP.

Haakana et al. [18] developed a methodology to promote the operation of CHP in the DA and balancing markets. It was tested with price data of the respective energy and power markets. Results showed that the participation in the balancing markets can be profitable, adjusting the electrical power may cause challenges to the heat delivery, because heat production is not constant, which poses a risk for the operation.

Beiron et al. [71] analyzed how the new market conditions impact the operational pattern and revenue of a CHP integrated with a TES. Five operational modes: conventional CHP, heat-only, CHP plus frequency response, condensing, and condensing plus frequency response were included. It was concluded that the electricity price profile impacts both the revenue and operational patterns and high average electricity price and price volatility result in increased profitability of product and flexibility.

4. Measures to improve the flexibility provided by CHPs

Flexibility provided by CHPs can be improved through retrofitting existing CHPs with new technologies. For example, the conversion of power into fuels via power-to-gas or utilization of heat in processes to produce alternate fuels can increase the short-term to long-term flexibility in CHPs. The integration of power to heat technologies is another option to decouple the heat and power generation. This section presents the features of available technologies.

4.1. Heat pumps (HPs)

A HP extracts heat from a medium with relatively low temperature (heat source) and upgrades it to a higher temperature by using electricity. It consists of two heat exchangers for evaporation and condensation of a refrigerant, a compressor driven by electricity and an expansion valve. Depending on both the ambient temperature and the indoor temperature, the HP can achieve an efficiency over 100%, which is higher than other Power-to-heat (P2H) technologies, such as electric boilers.

Most HPs are only capable of delivering heat at temperatures around 80 °C, but some high temperature HPs can produce heat at temperatures up to 130 °C [17]. The capacity of HPs ranges from 2 kW_{th} for single-family houses to 30 MW_{th} for industrial applications that can be integrated in DH. The main technical features of HPs are detailed in Table 10 [23].

HPs have fast reaction times and can vary their power consumption within seconds. It is also possible to switch on/off quickly. Moreover, TES can also be integrated with HPs to provide more flexibility services [79]. HPs can participate in ID and balancing markets as it can achieve the technical requirements rather quickly [80],[81]. For instance, HPs are capable for participation in continuous trading until 15 min before delivery. However, the ID market participation has higher technical requirements and the participation of HPs is only possible via an aggregator.

There are studies focusing on the integration of HPs to improve the flexibility in CHPs [76–82], some of which are summarized in Table 12. In general, most of works focused on the DA market; while fewer studies consider balancing markets. For example, based on the projected DA market price in Nordic region, Blarke & Lund [82] concluded that large scale HPs have abilities to increase the flexibility in CHPs; however, there are uncertainties related to operational performance and financial constraints of HPs that need to be resolved. Kiviluoma & Meibom [85] pointed out that even though HPs can increase the flexibility in CHP, their high investment costs may limit their integration. Münster et al. [83] and Blarke [84] reported that it is feasible to use HPs when the electricity prices are lower. Technology couplings of HPs with EB and TES in CHPs have shown more feasibility than standalone HP integration with CHPs. There are also a few of works investigating the benefit from participating balancing markets, such as FCR, aFRR and mFRR. Bhattarai et al. [86] reported that although HPs can provide balancing services, their operation is highly dependent on thermal demand, so dispatch optimization is required for economical benefits. In addition, considering the mechanical components of HPs, too many start-ups/shut-downs can increase abrasion and, hence, lower the lifetime or generate additional maintenance costs [87].

There are also many studies focusing on the flexibility provided by the combination of HPs and TES (HP+TES) [82–86]. Christidis et al. [88] investigated the flexibility in a CHP in the DA market. It was concluded that HP+TES can expand the operation capabilities of the studied CHP and offer new opportunities to take advantage of fluctuating electricity prices. However, no constraint on ramp rate was considered. Nuutinen and Graziano [90] studied the flexibility provided by HP+TES in Italian DA when coupled with a CHP. It allowed CHPs to ramp up or down its operation . Blarke and Dotzauer [91] evaluated the flexibility in a combined cycle based CHP. The production of CHP integrated with HP+TES was optimized for the DA, which results showed an increased benefit. However, ramp rate was not considered. Levihn [92] and Gao et al. [89] studied the potential to reduce the curtailment of VRE when integrating HP+TES in a CHP based on DA market without considering the ramping capability. It was found that the coupling can reduce the operating costs and curtailment.

4.2. Electric boilers (EBs)

An electric boiler (EB) is a device that uses electricity to generate steam. EBs can provide heat for space heating and industrial processes. The classical EB mainly consists of an insulated tank, thermostats, electric heating elements, anode rod, inlet/outlet pipes and some valves. EBs are available in various sizes and capacity (from 4 kW to 2 MW) [23],[93].

There are two types of EBs: resistance and electrode ones. Resistance EBs can be used for both individual heating systems and DH, whereas electrode EBs are only used for DH due to their larger capacities. Electrode boilers can provide warm or hot water as well as steam up to 300 °C and 30 bar with efficiencies above 99% and capacities of 5–60 MW. Flexibility parameters of both types of EBs are presented in Table 11.

Integrating EBs in CHPs can provide demand side flexibility, especially when associated with storage [94]. They can facilitate the accommodation of large shares of VRE. Their quick response speed and long availability are an important asset for P2H. EBs are also easy to maintain. EBs are well established in Scandinavia and Germany mainly due to electrical grids coping with growing shares of VRE.

Table 11
Technology Factsheet and flexibility parameters of resistance and electrode EBs [23].

Boiler type Parameter	Resistance Value	Electrode Value
Power output, MW_{th}	0.005–10	5–60
Operating temperature level input, °C	10–110	10–110
Operating temperature level output, °C	30–140 (steam possible; however, not common)	water: 70–140, steam: <300 at 45 bar
Net thermal efficiency, %	99	99
Operating range, % of load	1–100	1–100
Ramp rate up/down, % power/min	100	100

Table 12 summarizes some studies about the flexibility services provided by EBs. Most efforts were focused on the DA market. It can be concluded that the integration of EBs can lead to a remarkable increase in benefits. Even though the number of works studying the participation in the balancing markets is limited, EBs still demonstrate the potential to increase the flexibility provided by CHPs, due to their features of high ramp rates.

Similar to HPs, EBs are often combined with TES (EB+TES), which can achieve a bigger flexibility [89–94]. Examples are also listed in Table 13. According to Castellanos et al [97], EBs alone can only provide limited flexibility; however, coupling of TES with EBs showed higher flexibilities as it allows the storage of excess heat during off-peak hours. Lepiksaar et al. [95] examined the flexibility of a CHP integrated with EB+TES. It was claimed that using P2H together with TES will help improve CHP flexibility, but no detailed analysis based on real market prices was provided and no ramp rate was considered. Yu et al. [98] integrated the flexibility in a CHP with EB+TES. They performed the optimization on integrated process and found that the ramping capability of such a system can be increased, but no result was specified. Sinha et al [99] and Li et al. [96] optimized the operation of a CHP integrated with EB+TES for the DA market, both of which demonstrated an increase in profits fron 17,000 CNY to 131,000 CNY. Huang et a. [100] showed that the integration of EB+TES in CHPs can reduce the curtailment of wind power in the range of 6.3%-16.3% and the primary consumption of fuel to up to 2%.

4.3. Conversion to multi-energy systems (MESs)

It has been well recognized that decoupling the heat and power production is the key to improve the flexibility of CHPs. Therefore, if CHPs can be converted to MESs, the flexibility can also be improved.

4.3.1. Integration of electrolysis and fuel cells

The integration of hydrogen production through electrolysis can improve the flexibility in CHPs. The excess power, in case of high power production through VRE or when the electricity prices are low [117], can be used. Electrolyzers normally have fast ramp rates with very short start-up time [118]. Produced hydrogen can be stored and used to produce electricity via FCs [119], which convert chemical energy of hydrogen into electrical energy through electrochemical reactions. Similar to electrolyzers, high ramp rates of FCs make them suitable to provide ancillary services such as FCR, aFRR, and mFRR. FCs have fast ramping capability of 50–90% in 1 sec [120]. However, the power capacity and operating hours of commercially available FCs are low, which makes them suitable only for small scale applications. Lower capacity and high replacement costs make FCs expensive, which is not economically competitive at present [121]. Main flexibility parameters of two types of commercially available electrolyzers and FCs are presented in [122]. Technology factsheet and flexibility parameters of some electrolyzers and FCs are listed in Table 13.

There are some studies focusing on using electrolyzers to participate in DA, ID and balancing markets [68],[118],[123], and [124]. Main findings are summarized in Table 14. According to Suarez et al, electrolyzers can provide FCR and FRR services [118]. Eichhorn [123] optimized the operation of PEM electrolyzer in Austrian DA, ID, and balancing markets. They reported that the PEM electrolyzer was able to provide FCR, aFRR and mFRR, which can generate additional revenues. They further showcased that unpredictable market movements can hinder the willingness of market to involve in the hydrogen production through electrolysis. Larscheid et al [124] investigated the participation of a 10 MW electrolyzer in German balancing market. Results show that positive aFRR and mFRR were most profitable; however, the electrolyzer must run between 6.5 MW to 10 MW. On the contrary, the electrolysis process was not able to generate profits when providing negative aFRR and mFRR. The electrolysis process must be synchronized with the electric grid for FCR provision to give profit as they act as reserve for FCR provision and cannot operate in full load.

You et al [68] also reported that electrolysis can provide flexibility through participation in balancing markets, with high potential in aFRR and mFRR and medium potential in FCR, especially when only active electricity regulation is required. Meanwhile, they also stated that RR is the most technically viable option as it requires slower response than others and can be implemented with higher capacity of electrolysis process. Jørgensen et al [125] studied hydrogen production via electrolysis when it takes part in DA market for electricity, however the price of hydrogen can 0.41 Euro/m^3. Kroniger et al [126] also studied the flexibility of electrolyzers taking part in electricity spot market. Guinot et al [127] optimized the profit when an electrolyzer provides balancing services in French market. Mansilla et al [128] reported that it is possible to produce hydrogen at lower price when the electrolyzer is connected with grid balancing services.

The existing works have demonstrated the high potential to improve the flexibility if electrolysis and FCs can be integrated in CHPs. However, few works have been done to assess the CHP coupling with electrolysis and FC. Although power-to-hydrogen that integrates electrolysis with CHPs can increase the operational flexibility and operating hours, it was also found that the integration can increase the operational costs [[117],[129]]. In addition, the electrolysis process and the operation of FCs can produce a large amount of heat, which can also be recovered and used for DH. For example, Tiktak et al. stated that about 90% of heat produced in electrolyzer stack can be recovered [130]. Ottosson et al. have investigated the feasibility to use the heat from the PEM electrolyzer to for DH network [131] used the excess. Such recovered heat can further improve the benefit of DH.

4.3.2. Integration of pyrolysis and gasification

The integration of gasification and pyrolysis in CHP is another potential way to convert CHPs to MESs, which can provide more flexibility [132]. Gasification occurs with partial amount of oxygen, which can be present in the form of air, steam or pure oxygen. Gasification produces syngas containing mainly CO, H_2, CH_4, CO_2 and H_2O. Syngas can be combusted directly for heat and power production or be further processed into different gaseous and liquid biofuels [133]. Pyrolysis normally occurs in the absence of oxygen and produces liquid bio-oil, solid biochar, and syngas. Bio-oil can be further upgraded into liquid biofuels or combusted to produce heat and power [134]. Both processes are endothermal, which can utilize the excess heat from CHPs during off-peak hours. The produced biofuel can be used in engines or turbines to produce electricity and heat when the demands are high. Such an integration can increase the operating hour, overall efficiency, flexibility and profitability of CHPs [129].

There are two ways for the integration of gasification: (I) the gasifier is added as a sub-system of the CHP boiler where the needed heat is taken [135]; and (II) the gasifier replaces the boiler and a gas turbine cycle, or a combined cycle (IGCC) is integrated to use the produced syngas for heat and power production [136].

Table 12
Increase in flexibility of CHPs with integration of TES/HP/EB through market participation.

Ref	Flexibility services	Implemented technologies	Work description	Main findings	Note
Thermal energy storage (TES)					
[71]	Case 1: DA Case 2: FCR	TES from 3 h to 1 week with an 50 MW waste fired CHP	Different market scenarios and the impact of technical aspects on the operation of the plant was analyzed, with plant revenue and utilization considered as KPIs	Flexibility can increase annual revenue up to 1.5 M€	Capital investment costs were not included and operational costs were used for economic performance
[101]	DA market	TES with CHPs	Optimizing operation to evaluate the economic incentives through participation in the spot market	An increase in revenue to 2.5 M$ from 1.1 M$	No ramp rate was reported
[102]	DA market	30 MW_e and 100 MW_{th} CHP with TES integrated	The integration was optimized using revenue as objective function	Approx. 100 MEuro increase in revenues.	Ramp rate of CHP and TES was considered fast and not included in modeling
[103]	DA market	5 MWe CHP with 1500 m^3 TES	The optimal TES volume was determined	An increase annual revenue of 311,000 € to 460,000 €	-
[104]	DA market	4 MWe CHP with 650 m^3 TES	CHP operation was optimized	Flexibility depended on spot prices of electricity. TES increases flexible operation and reduced the payback period from 9 to 5 years.	Stability of spot markets was vital to increase flexible operation of CHPs
[105]	DA + ID markets	1265 MWe CHP with 0–10,000 MWh TES	CHP operation was optimized	An increase in efficiency from 86% - 90% with TES. Cost saving up to 4.579 M€	–
[106]	DA market	307 MWth CHP with 3600 m^3 TES	CHP operationwas optimized	Up to 1.8 MEur savings. An increase in electricity production from 38.2 GWh to 39.6 GWh.	No ramping was considered
[107]	DA market	33 MWe CHP with 18 MW TES	The size of TES and the operation of coupling were optimized	Up to 3% reduction in heat generation costs.	–
[108]	DA market	43 MWe CHP with 25 MW TES	The operation was optimized to minimize operational costs	TES led to an annual saving of 16.5% from base case .	–
[109]	DA market	300 MWth CHP with TES	The flexible operation range was investigated	The flexible operation range was increased up to 42.4 MW for TES.	No ramp rate was considered in modeling
[68]	DA market	300 MWth CHP with TES with maximum steam extraction of 400 t/h	The ramp rate was studied	An increase in 6% of ramp rate	–
[72]	DA, Balancing markets (mainly aFRR and FCR)	CHP with TES*	Dynamic operation of CHPs with TES was examined for participating in DA and balancing market	TES integration was able to fulfill aFRR and desired power levels were achieved in 2–3 min	-
[110]	DA and balancing market	200 MWth CHP with 1200 MWh TES	Startup costs, minimum downtime and maximum load gradients for CHPs were studied with the consideration of fuel consumption, expenditure and increase in revenue	TES can increase the power generation of CHPs at higher electricity prices and low heat demand	No ramp rate was considered in modeling
[111]	Balancing market	300 MWth CHP + TES	The operation of CHP was optimized regarding, primary energy consumption and payback time	The heat output of the CHP can increased by50 MW at any given power output level.	Ramp rate was included in the model
[66]	ID and FCR	700 MWth CHP + TES	Dynamic simulations were performed	The integrated energy storage enhances the frequency control supply by ±2.8%	Ramp rate constraint was used in the model
Heat pumps (HPs)					
[112]	DA market	330 MWth CHP with 100 MW HP	The operation of CHP was optimized with coupling of HP and EB	Flexibility operation range increased from 70 MW CHP alone to 130 MW for CHP+HP system	No constraint on ramp rate was used in model
[109]	DA market	300 MWth CHP with HP	The flexible operation range was examined	The flexible operation range up to 71.6 MW for HP	No ramp rate was considered in modeling
[113]	DA market	80 MWe CHP with 30 MW HP	CHP operation was optimized to save costs.	0.34 MEuro savings for HP annually	No ramp rate was considered in modeling
[110]	DA and balancing market	200 MWth CHP with 100 MW HP,	Start-up costs, minimum downtime and maximum load gradients for CHPs were studied with the consideration of fuel consumption, expenditure and increase in revenue	Power generation of CHPs was increased i at higher electricity prices and low heat demand	No ramp rate was considered in modeling
[114]	DA, ID, and balancing market (FCR, aFRR and mFRR)	DH + distributed HP* installed in buildings	Operation of coupling was optimized	mFRR are found to be the most suitable service for using HPs as demand response	No ramp rate was considered in modeling

(*continued on next page*)

Table 12 (*continued*)

Ref	Flexibility services	Implemented technologies	Work description	Main findings	Note
Thermal energy storage (TES)					
[29]	DA, ID, FCR, aFRR and mFRR	25MWe CHP + HP	Modeling was performed to assess whether the coupling can participate in spot and balancing market	Integration can participate simultaneously in both aFRR and FCR while operating within the technical operational limits when HP and EB were coupled with CHPs	Ramp rate constraint was not used in model
Electric boilers (EBs)					
[109]	DA market	300 MW CHP with EB	The flexible operation range was determined	The flexible operation range up to 124.2 MW for EB	No ramp rate was considered in modeling
[112]	DA market	330 MWth CHP with 100 MW EB	The operation of CHP with coupling of HP and EB was optimized	Flexibility operation range was increased from 70 MW CHP alone to 189 MW CHP+EB system	Ramp rate limit was not used in model
[113]	DA market	80 MWth CHP + 40 MW EB	The operation of CHP was optimized to save costs	0.11 MEuro savings for EB annually	No ramp rate was considered in modeling
[115]	DA market	2130 MW demand of cumulative heat demand from CHPs in Germany with 1000 MW EB coupling	The operation was optimized to maximize cost saving.	With flexible bidding structure and power from wind and solar plants , the probable savings amounted to be 52 MEuro	Ramp rates were not included in model
[94]	DA + ID market	CHPs in Norway, Denmark and Sweden with integration of EB	Flexibility potential of CHP integrated with EB was assessed	EB can provide flexibility when operated under spot market electricity prices; however, the potential benefits with current regulation in place were low.	No ramp rate was considered in modeling
[111]	Balancing market	300 MWth CHP with EB	The operation of CHP was optimized regardings, primary energy consumption and payback time	EBs can reduce the power curtailment. The heat output of the CHP can be increased by 50 MW at any given power output level.	Ramp rate was included in the model
[29]	DA, ID, and balancing market (FCR, aFRR and mFRR)	25MW CHP + EB*	Modeling was performed to assess whether the coupling can participate in spot and balancing market	Integration can participate simultaneously in both aFRR and FCR while operating within the technical operational limits when HP and EB were coupled with CHPs	Ramp rate constraint was used in model
[116]	Balancing market (FCR, aFRR, mFRR)	100 MW CHP with 10.55 MWe flexible load from EB	The operation of coupling and ramp rate were optimized	Integration of EB with CHPs mostly provided downward flexibility. EB can also fulfill FCR with fast ramp rates; and it was not economically feasible when the CHP operated only in energy markets	No ramp rate was considered in modeling

* size not given

Table 13
Technology factsheet and flexibility parameters of alkaline water electrolyzers, polymer electrolyte membrane (PEM) electrolyzers, PEM and Alkaline based fuel cells (FCs) [122].

	Electrolyzers		Fuel cell (FC)	
	Alkaline water electrolyzers	PEM electrolyzers	PEM FC	Alkaline FC
Power capacity	1.8 kW to 53 MW	0.2 kW to 11 MW	1 kW – 100 kW	1 kW – 100 kW
Operation range, %	15–100%	0–100%	0–100%	0–100%
Start-up (warm-cold)	1 -10 minutes	1 sec – 5 sec	In seconds	In minutes
Ramp rate, %power/sec	0.2–20	100	50–90	0.2–20
Shut down time	1–10 minutes	Seconds	In seconds	In minutes

Several authors have studied the integration of gasification with existing CHPs [4] [137] [138–140]. Gustavsson et al. [138] utilized the excess heat from CHP in the retrofitted gasification process to produce liquid biofuels. Heyne et al. [139] used pinch analysis to determine the optimum integration of gasification with CHPs. Salman et al [135] utilized the excess heat from the steam cycle of a CHP in three different gasifiers and reported that dual fluidized bed gasifier has capability to operate the CHP with minimal impact on its performance. The CHP integrated with gasification process for biomethane and liquid alternative biofuels production can increase the operational and product flexibility of the whole system without compromising the annual heat and power demand [[135],[136],[129]]. However, the production of biofuels alongside power and heat allows the provision of aggregated energy resources that can be utilized in a wide range of applications. Production of biofuels alongside heat and power from CHPs also enhances the flexibility in terms of products and operation as CHPs can optimize their production by selecting appropriate product as per market demand to enhance profits [141]. A 20 MW gasification-based CHP which also produces biomethane was demonstrated in Sweden. The plant showed flexibility towards fuel however, its start-up time was high and ramping capability was lower [142].

The flexibility in IGCC is found to be comparable with gas turbine based CHPs [143]. IGCC based CHPs have hot start-up of 6–8 h and cold start up time of 80–90 h. They have a ramp rate around 3–5%/min and minimum load of 60% [144]. The operational range of IGCC CHPs is from 50–90%. Coal based IGCC plants can have a power capacity of

Table 14
Potential of electrolyzers to provide flexibility through participation in energy markets.

Ref	Grid services	Main findings	Notes
[68]	DA, balancing markets	Alkaline and PEM electrolyzers were capable to provide almost all kind of grid services. However, electrolyzers had high potential to provide aFRR and mFRR compared to FCR.	–
[125]	DA	Electrolyzer was able to produce hydrogen at 0.41 Euro/m^3 when electrolyzer participated in DA market.	Demand of hydrogen in future will be vital for electrolyzers to produce hydrogen at competitive prices
[118]	Case 1: aFRR; Case 2: FCR	Electrolyzers have fast ramp rates so they can participate in balancing markets and help curtail electricity. FCR was the most attractive option than aFRR.	Electrolyzers can also provide voltage control and congestion management
[123]	Case 1: DA; Case 2: FCR; Case 3: aFRR	Electrolyzers were able to provide flexibility through participation in grid balancing services (aFRR, FCR) and can increase revenues.	No proper data and forecasts available for FCR and aFRR
[124]	Case 1: DA; Case 2: FCR; Case 3: aFRR Case 4: mFRR	aFRR and mFRR were the most promising options for electrolyzers. In addition, markets with high share of renewable energy resources offered more opportunity to provide grid services.	Operational and regional market constraints can affect the revenue gains for electrolyzers participating in grid markets
[127]	Investigation of hydrogen production from electrolyzers when participating in balancing services	Revenues for hydrogen production were highly dependent on market constraints when electrolyzers were connected to grid balancing services.	Study used French grid market conditions
[128]	Determination of hydrogen production costs from electrolyzers when participating in DA and balancing services	Electrolyzers participating in DA and balancing market can produce hydrogen at lower costs	French market conditions were used

as high as 700 MW with stable operation [[141],[145]]. The flexibility in IGCC is mainly limited by the air separation unit. But this can be solvedby installing the storage of liquid oxygen onsite [143]. IGCC based CHPs have higher efficiencies that can also offset thehigh start-up costs thus allowing it to provide flexibility with more economic benefits [146]. It was also verified that the multiple products from IGCC with respect to market signals can increase its flexibility and profits at the same time [147].

The studies integrating pyrolysis in CHPs have been mostly limited to base-load analysis . Kohl et al. [[148],[149]] integrated the pyrolysis by taking the heat directly from the boiler. They reported the increase in energy efficiency and operational hours of process integration on both design and off-design bases. Daraei et al [150] studied the integration of pyrolysis with a CHP and reported that such an integration can increase the operational range of CHPs by 2%. Onarheim et al [151] integrated pyrolysis with the fluidize bed boiler of a CHP and reported that integration reduces the primary fuel consumption and cogenerate the liquid bio-oil from pyrolysis.

5. Discussions

5.1. Technology selection to improve the flexibility provided by CHPs

Through matching up the requirements of flexibility services with the technical features of different technologies, the potentials to improve the flexibility of CHPs are summarized in Table 15. Here, the reference CHP consists of a biomass fired boiler and backpressure STs. Such a CHP mainly participates in DA and ID, even though it can also potentially provide balancing services such as, FCR, aFRR, and mFRR services. Changing backpressure STs to condensing STs can reduce the dependence of power generation on the heat demand. Therefore, it can allow larger operation range, which can favor ID, FCR and mFRR. However, they do not have higher ramp rates and faster start-up and shut down which are required to improve aFRR. It is similar for gas boilers and TES. Since the integration of TES can decouple the generation of electricity and heat more effectively, it can achieve larger improvements. Comparatively, HPs and EBs have larger ramp rates and operation ranges, which are more suitable to provide aFRR. Moreover, electrolyzers and FCs also have high ramp rates and fast start-up and shut down , which make them applicable to improve the ancillary services in balancing markets. However, there is still a lack of literature that assesses the performance of the integration of electrolyzers and FCs in CHPs about the participation in DA, ID and balancing markets. For the integration of gasification and pyrolysis in CHPs for polygeneration of biofuels along side heat and power can be identified to improve the performance of CHPs in participating in ID, and possibly balancing markets as well, due to the products of syngas and bio-oil, which enable the applications of engines and turbines. Nevertheless, no existing research has verified the benefit. In addition, coupling technologies can achieve a greater flexibility, such as HPs+TES and EBs+TES. However, considering the increased capital cost, the economic feasibility still needs to be justified and optimization is also needed to size the capacities for the coupled technologies to maximize the benefit.

5.2. Knowledge gaps

Although improving the flexibility of CHPs has attracted much attention, clear knowledge gaps and challenges can still be found in the open literature.

Some flexibility services, such as aFRR, FCR and mFRR, have specific requirements on the response time and bid sizes, which can be reflected by the defined KPIs, including ramp rate, operating range and start-up time; however, such KPIs are yet available for some technologies, especially the coupled technologies. This has hindered further studies for example: cogeneration of biofuels from the integration of pyrolysis and gasification in CHPs and the integration of FCs for heat and power production. Moreover, the fast start-up capability is crucial for providing flexibility services, but such a non-standard operation will induce more thermal stress in critical components e.g., STs, GTs etc. which leads to increased fatigue damage and a greater reduction of lifetime. This will require more frequent maintenance, which will consequently induce higher costs. Therefore, conventionally, non-standard operations such as fast starts have been avoided. Aggregation can help address the technical limitations of the individual units that provide flexibility services.

Table 15
Summary of reviewed technologies and their potential to improve the flexibility provided by CHPs ('-'means no change; '↑' means improvements).

Reference CHP	DA Implemented	ID Implemented	aFRR Possible	FCR Possible	mFRR Possible
Condensing STs	–	↑	–	↑	↑
Gas boilers	–	↑	–	↑	↑
TES	–	↑↑	–	↑↑	↑↑
HP	–	↑↑	↑	↑↑	↑
EB	–	↑↑	↑	↑↑	↑
Polygeneration	–	↑	uncertain	uncertain	uncertain
Electrolyzers/FCs	–	↑↑	↑	↑	↑
HP+TES	–	↑↑↑	↑↑	↑↑	↑↑
EB+TES	–	↑↑↑	↑↑	↑↑	↑↑

For example, one unit may suffer from slow start-up and insufficient ramping capability, but the aggregation of several units may provide sufficient power within the required period of time [[152],[153]].

TES has been identified as an effective measure that can improve the flexibility of CHPs. However, current studies that optimize the operation of TES regarding the provision of different flexibility services are mainly based on energy balance, which implies that the requiredheat can always be extracted from TES or the additional heat can always be saved in TES. Nevertheless, the capability of charging and discharging of TES depends on many factors, such as the temperature of heat, the amount of heat and the state of charge. No constraint has been added to consider such influencing factors.

Even though the integration of electrolyzers and FCs shows the capability of improving the flexibility of CHPs, there haven't been many works evaluating the potential benefits when participating in balancing markets. For the integration of gasification or pyrolysis, most of the studies focused on the efficiency of coupled processes and flexibility in terms of product selection and product planning; while no study can be found regarding analyzing the potential flexibility improvement of CHPs, in terms of ramp rate or operation range considering the ID, DA and balancing markets. Furthermore, there is an absence or difficulty in obtaining real plant data for gasification and pyrolysis which makes their modeling and simulation difficult to validate.

To motivate CHPs to provide flexibility, more demonstrations about the potential benefits from different markets are still needed. As summarized in the previous sections, most of studies focus on DA and ID markets. There are limited number of studies about other markets, such as aFRR, FCR and mFRR which are conducted for the conventional configurations of CHPs. In order to promote the renovation of CHPs, it is of great importance to illustrate how CHPs can make profits from investing technologies that can improve the flexibility, especially when new technologies with faster ramping capabilities and shorter start-up time are integrated. MESs are promising sources of flexibility, not only for DA and ID markets, but also for balancing markets; whereas their profitability still remains uncertain due to lack of studies. In addition, countries have different rules, and the optimal strategy for CHPs to provide flexibility will depend on the local power markets and its requirements. It is certainly interesting to compare the influence of different market mechanisms on the provision of flexibility, which is significant to develop new business models and renovate the energy market.

The technology readiness level (TRL) of reviewed technologies is also a hindrance for their mass scale implementation. Such as, gasification and pyrolysis have TRLs of 4–6 with high capital and operating expenses [154]. The coupling of these processes with CHPs can be more complex as compared with TES, HPs, and EBs, which also make it difficult for CHPs to use gasification and pyrolysis to improve their flexibility. Even though electrolyzers and FCs are suitable to couple with CHPs to increase their flexibility, unpredictable hydrogen prices and lower efficiencies and operating hours of electrolyzers and FCs can prevent CHP stakeholders to consider them. The integration of HPs and EBs will add investment costs to exiting CHPs. Currently, the HP has higher investment costs, which are up to 500–1800 Euro/kW$_{th}$, than EBs, which costs are around 30–150 Euro/kW$_{th}$. However, few studies have considered their capital costs.

Conclusions

The technologies that have commonly been or could be adopted in conventional combined heat and power plants (CHPs) have been reviewed to characterize their capabilities for providing different flexibility services, such as the participation in day-ahead market, intraday market, and balancing markets. Potential benefits from the provision of flexibility can be identified through optimizing the operation of CHPs. It can be concluded that to be more flexible and profitable, CHPs are expected to be able to operate in a larger load range with higher load-change rates, and even operate in start/stop mode with full turndown and fast re-start at high efficiency levels. However, clear knowledge gaps exist in the literature. For example, the concrete technical features of flexibility, i.e. ramp rate, operation range etc., for some technologies, such as thermal energy storage, still remain unclear, which can lead to a bigger uncertainty in the operation optimization. In addition, even though new technologies and technology couplings are emerging to increase the flexibility in CHPs, such as electrolyers, FCs, pyrolysis and gasification, few studies have investigated the flexibility they can provide. Furthermore, some flexibility services, such as aFRR, FCR and mFRR, have specific requirements on the response time and bid sizes which vary in different regions and markets, which may further affect the flexibility provision potential of CHPs.

Declaration of Competing Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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