Role of thermal technologies for enhancing flexibility in multi-energy systems through sector coupling: technical suitability and expected developments

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Abstract: Thermal power generation technologies are widely used for electricity production, for heat provision in district or process heating systems, and for combined heat and power generation. In most cases, thermal technologies are heat driven and electricity is produced as a by-product, thus resulting in a non-flexible behaviour of the electricity production. Modern power grids are characterised by an increasing share of renewable leading to a need for enhanced and flexible ways of controlling the power flow. To provide services to the power grid, thermal generating technologies may be used in a more efficient way, coupled to gas and heat storage systems or aggregated in virtual power plants. Several technical factors determine which technologies are suitable for flexibility provision, including power ranges, start up times and ramp rates. In this work, carried out in the frame of the MAGNITUDE H2020 project, the technical characteristics of thermal sector-coupling technologies were analysed using data from the seven real-life project’s case studies. The technical suitability was determined based on the product requirements in selected European power markets for the provision of identified system services. Expected future developments and trends were highlighted well.

1 Introduction

1.1 Need for more flexibility to operate the power network

The increasing share of volatile distributed resources, digitalisation, increasing share of renewable energy (Fig. 1) as well as the greater interconnection of heat, gas and power markets are the key drivers for the evolution of the power system. In recent years, it can be observed that production and demand patterns are becoming more erratic. To operate the power system in a reliable and secured manner, flexibility is required, e.g. to compensate coming fluctuations from renewables power generation or to respond to voltage or frequency deviations (Fig. 2). As an example, thermal systems [power-to-heat (PtH), heat-to-power] may be utilised to overcome the oscillating behaviour of wind or solar production patterns as they are characterised by a higher inertia than electrical ones. Flexibility as the ability to adjust generation or consumption in the presence of network constraints to maintain a secure system operation for reliable service to consumers’ is defined in [1].

1.1.1 Needs of various needs of flexibility: Flexibility is required to address various grid management issues. Usually, a distinction is made between short-term and long-term flexibility needs:

• The first refers to the short-term balance of energy supply and production for maintaining the stability of the power system (frequency containment on a national/regional level and voltage control at a more local level).
• The latter corresponds to the medium-to-long-term equilibrium between supply and demand in energy systems characterised by high seasonal fluctuations due to a high penetration of renewable energy resources, such as electricity from photovoltaic (PV) panels in the summer.

1.1.2 Untapped potential of new flexibility options: Today, some conventional assets, such as gas turbines and pumped hydroelectric energy storage, that are able to react quickly to a grid issue, provide short-term flexibility to the power system while others, such as underground thermal energy storage (TES), provide seasonal flexibility. However, with the advent of smart grids allowing for greater control of the energy assets, the roll-out of advanced metering infrastructure and storage technologies as well as the development of new market designs, additional alternatives for flexibility provision are to be considered. Those can be ranked in the following four categories as presented in [4]:

(i) Demand-side measures (DSMs): Modification of consumer demand through price signals or behavioural change. The aim of DSM is to reduce demand during consumption peaks in order to avoid grid congestion issues or the ramp up of additional power plants to meet growing demand.
(ii) Electricity storage: Electric batteries can be used to increase the self-consumption rate of PV-battery system at household level. Furthermore, bigger storage systems in the MW range installed nearby substations can help in maintaining grid stability through charging or discharging energy from or to the grid.
(iii) Supply-side measures: Development of highly efficient and flexible combined heat and power (CHP) technologies allows for increased provision of balancing energy. The curtailment (dispatch down) of intermittent energy sources, such as wind and solar plants, is another supply-side option to tackle local congestions or system-wide issues.
(iv) Sector-coupling technologies: Technologies that allow conversion between heating/cooling, gas and electricity and can provide flexibility services to the power grid, such as heat pumps (HPs), electric boilers or combined cycle gas turbine (CCGT).

1.2 Objectives of the study

This paper investigates how to enhance flexibility provision in multi-energy systems (MESs) through sector coupling and heat storage technologies. The most promising technologies in terms of flexibility provision are characterised and described according to key parameters such as power ranges, start up times and ramp rates to assess their capability to provide the most relevant system services. The assessment is based on a technical, economic and regulatory multi-criteria analysis with a focus on the West-
European power markets. Finally, a discussion is given on current technology bottlenecks, future trends and drivers and electricity market boundaries.

The services considered in this paper are presented briefly in Table 1.

2 Main flexibility characteristics

2.1 Technology review

In the past, thermal technologies were installed mainly to produce heat and/or electricity [6]. Main focus was on combustion of fossil fuels coal, oil and natural gas. This had a big impact on the growth of efficiency of thermal generating technologies, first solid- and then liquid-fuel-based ones. This increase of efficiencies was accompanied by an increase of size. However, due to growing role of renewables sources of energy, these trends have significantly changed. Currently, besides being highly efficient (energetically and environmentally), technologies have to be very flexible and no longer large in terms of capacity, thus allowing them to play a key role in balancing power grid. Thermal power generation technologies are widely used for electricity production via steam processes, for heat provision in district or process heating systems, as well as CHP generation. The heat production is strongly coupled with heat demand, both for district and industrial uses. Thus, resulting in a non-flexible behaviour for the electrical output. Therefore, power and heat production have to be decoupled to provide flexibility, e.g. it can be temporarily done by means of heat storage, electric boilers and HPs [7–9] in industrial and district heating (DH) networks. In addition to that, CHP should be operated in a full cogeneration mode to consider all electricity produced as CHP electricity; otherwise, non-CHP electricity is generated. Full cogeneration mode means that units such as CCGTs and steam condensing extraction turbines have to be operated with the total efficiency at least at 80%, and technologies such as steam back pressure turbines, gas turbines, internal combustion engines, microturbines, Stirling engines, fuel cells, organic Rankine cycle (ORC) have to reach threshold at least 75% of the total efficiency [10, 11]. Besides that an important value is PtH ratio that is characteristic of each CHP unit and shows split between electricity from cogeneration and useful heat when operation in full cogeneration mode, it ranges from 0.45 for steam turbines to 0.95 for CCGT with heat recovery. It is clear that the units with low PtH ratio will be much more impacted by the flexible operation than those with higher values. Therefore, in future, not only efforts to utilise the surplus of heat generation (e.g. heat storage) shall be carried out, but also to maintain high efficiency a modular approach should be favoured.

Several factors determine which technologies are suitable for sector-coupling purposes, including end-use and conversion energy efficiency, temperature levels that can be reached, possibility to bridge local energy demand with generation, environmental impact of the production and, not less importantly, value of the provided flexibility. Table 2 details the technologies, and related energy-conversion chains, that have been reviewed in this study.

2.2 Power consumption

2.2.1 Heat pumps: HPs transfer heat from a low-temperature source (air-ambient or exhaust-ambient, water-ambient from the underground, lakes, rivers, seas, sewage treatment plants or industrial processes and geothermal brine) to a higher-temperature sink. Applications are various: individual heating systems, DH, tertiary and industrial applications etc. HPs provide several units of heat per unit of electricity consumed, making them much more
Table 1 Most relevant system services to be provided by MESs [5]

| Needs                          | Services | Short description                                                                 |
|-------------------------------|----------|-----------------------------------------------------------------------------------|
| frequency control and         | FCR      | activated to stop a frequency deviation after the occurrence of an imbalance on the |
| balancing                     |          | European synchronous network                                                     |
| automatic frequency           |          |                                                                                   |
| restoration reserve           |          | active power reserve, which is automatically activated to replace the FCR after a |
| (aFRR)                        |          | frequency deviation and to restore the frequency to its nominal value             |
| manual frequency              |          |                                                                                   |
| restoration reserve           |          | active power reserve, which is manually activated after a frequency deviation to    |
| replacement reserve           |          | complement or to release the aFRR if the demand for secondary control reserve is    |
|                               |          | too high                                                                           |
| energy trades                 |          |                                                                                   |
| day-ahead energy trades/      |          | trading of electricity for the following day. Biggest market volume               |
| market                        |          |                                                                                   |
| intraday energy trades/        |          | to trade on the short-term energy volumes to be sold/purchased. Traded volumes      |
| market                        |          | currently increasing because of the development of intermittent energy generation  |
| system adequacy               |          | to contribute to the security of supply, avoid or postpone the unexpected accelerated|
| capacity requirement          |          | shutdown of old conventional plants and compensate prolonged outages of crucial     |
| mechanisms                    |          | assets. Currently existing under very different forms in Great Britain (GB), France  |
|                               |          | (FR), Spain (ES), Sweden (SE) and soon in Italy (IT)                              |
| congestion management         |          | measures taken when the forecasted or the real power flows exceed the physical     |
| re-dispatching mechanisms     |          | capability of the grid components                                                 |

Table 2 Selected sector-coupling technologies [12]

| Number | Technology         | Power consumption |
|--------|--------------------|-------------------|
| 1      | HPs                | Power output      |
| 2      | electrical boilers |                  |
| 3      | compression chillers| power-to-cold     |
| 4      | ORC                | heat-to-power     |
| 5      | steam turbines     |                  |
| 6      | gas engines        | gas-to-power      |
| 7      | gas turbines       |                  |
| 8      | thermal storage    | storage           |
| 9      | sorption chillers  | heat-to-cold      |

Table 3 Technology factsheet – HP [12]

| Parameter                        | Unit  | Value  |
|----------------------------------|-------|--------|
| power output                     | MWth  | 0.002–30 |
| operating temperature level input| °C    | −20+/+50 |
| operating temperature level output| °C   | 30–100 |
| minimum load                     | %     | 10     |
| controllable range               | %     | 10–100 |
| Coefficient of performance (COP)  | —     | 2–5 (practical) |
|                                 |       | 1–20 (theoretical) |
| cold start up time              | min   | 300    |
| hot start up time               | min   | 3      |
| ramp rate up/down               | % rom | 20     |
|                                 | power/min |        |
| specific investment costs        | €/kWth| 500–1800 |

efficient than other PtH technologies [13], such as the electric boilers described hereafter. The thermal capacity of HPs ranges from 2 kWth for single-family houses to 30 MWth for integration in DH and industrial processes. HPs provide usually temperatures in the range 40–90°C, but HPs development to provide higher temperatures is ongoing fast and some HPs providing heat in the temperature range 100–160°C and steam are already being tested and installed [14]. This development will broaden the field of application to many industrial processes and DH networks running with superheated water [15]. If HPs are part of a multi-source heating system, e.g. heat storage and/or boilers, they cover the heat supply at least partially, and can be switched on or off according to the electricity grid requirements. However, their flexibility potential is determined by the heat demand, or heat storage capability, of the overall heating system. HPs are usually not designed to switch on or off very often. Owing to the mechanical parts inside the HP, too many start ups/shutdowns increase abrasion and lower components (especially condensers and evaporators) lifetimes [16]. In the recent years, improvements have been done to run HPs more flexibly, e.g. via inverter technologies [17]. A major barrier to a wide deployment of HPs is the currently changing regulation on refrigerants. In more and more European countries, synthetic refrigerants based on fluorinated hydrocarbons are forbidden due to their strong global warming potential (GWP) effects. Therefore, new low GWP refrigerants are developed, tested and applied in HPs, e.g. ‘fourth-generation refrigerants’ (e.g. hydrofluoroolefines), NH₃, CO₂ or natural carbohydrates (often flammable, toxic or requiring higher operating pressures). However, their thermodynamic properties differ compared with previously used refrigerants, which require adaptation of compressors and exchangers to ensure the same performances [18]; so, further research and development (R&D) efforts are needed (Table 3).

2.2.2 Electrical boilers: Two types of electric boilers are available: resistance and electrode ones. The resistance boilers are usually used in individual heating systems, whereas electrode boilers are only implemented for DH due to their larger heat production capacities. Steam production for industry is also possible, but the specific costs increase significantly. There are no technical barriers, which prevent the use of electrical boilers for flexibility services provision. The complexity of the power control is closely connected to the thermal capacity, due to the amount of heating elements. A minimum electrical load is required to enable very fast ramp up times. Owing to high electricity price compared with the low gas price, provision of base-load heat via electric boilers is actually not economic so far. However, the flexible provision of heat is very common with electrode boilers, which are due to their minimal pipework and no heating surfaces – very well suited to fast ramping. The response times to full nominal capacity are very fast; a minimum load of about 1% nominal capacity is required to keep the boiler operational. 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. The precise controllability, the fast load gradient and the fully automatically controllable operation make it possible to control all types of regulating power: primary, secondary up to minute reserve capacity. Therefore, electrical boilers as a mature
technology are established well in Scandinavia and Germany to support electrical grids coping with growing shares of intermittent wind and PV generation. In Denmark, large boilers are used predominantly for primary grid regulation; so, the whole capacity of the boiler is bid in for negative grid regulation, thanks to the short ramp up times. In other countries, notably Germany, a market has developed for large electrode boiler in negative secondary regulation applications, i.e. absorbing power from the grid, but over longer periods. Small electric boilers are used to provide heat and domestic hot water for single and multi-family houses, but their sizes do not fit to market requirements for grid services provision unless aggregation is put in place (Table 4).

### Table 4 Technology factsheet – resistance heater and electrode boiler [12]

| Parameter               | Unit          | Resistance Value | Electrode Value |
|-------------------------|---------------|------------------|-----------------|
| power output            | MWh           | 0.005–10         | 5–60            |
| operating temperature   | °C            | 10–110           | 10–110          |
| input                   |               |                  |                 |
| temperature level       | °C            | 30–140 (steam)   | 45 bar          |
| operating temperature   | °C            | water: 70–140,   |                 |
| level output            |               | steam: <300 at   |                 |
| minimum load            | %             | 1                | 1–5             |
| controllable range      | %             | 1–100            | 1–100           |
| net thermal efficiency  | %             | 99               | 99              |
| cold start up time      | min           | 5 (but no common use) | 5               |
| hot start up time       | min           | <0.5             | <0.5            |
| ramp rate up/down       | % nom power/min | 100             | 100             |
| specific investment     | €/kWe         | 30–150           | 40–100          |
| costs                   |               |                  |                 |

### Table 5 Technology factsheet – compression chiller [12]

| Parameter               | Unit          | Air-cooled chillers | Water-cooled chillers |
|-------------------------|---------------|---------------------|-----------------------|
| power output (cold output) | kWh         | 0.1–1750           | 21–21,000             |
| temperature level output | °C           | −35/+5              | −45/+5                |
| minimum load            | %             | 20                  | 20                    |
| controllable range      | %             | 20–100              | 20–100                |
| energy efficiency ratio | (EER)         | 2.6–3.24            | 4.0–6.31              |
| cold start up time      | min           | 20–60               | 20–60                 |
| ramp rate up/down       | % nom power/min | 1.6–5% for         | 1.6–5% for             |
| (cooling)               |               | start up            | start up              |
| specific investment     | €/kWth        | 350–880             | 220–530               |
| costs                   |               |                     |                       |

### Table 6 Technology factsheet – single-stage steam turbine [12]

| Parameter               | Unit          | Single stage Condensing | Backpressure |
|-------------------------|---------------|--------------------------|--------------|
| power output            | MWe           | 0.1–6                    | 0.1–6        |
| operating temperature   | °C            | 150–500                  | 150–500      |
| level input             |               |                          |              |
| operating temperature   | °C            | 50–70                    | 100–400      |
| level output            |               |                          |              |
| minimum load            | %             | n.a.                     | n.a.         |
| controllable range      | %             | n.a.                     | n.a.         |
| net electrical efficiency | %           | 10–20                    | 3–15         |
| thermal efficiency      | %             | 0                        | <80          |
| cold start up time      | min           | n.a.                     | n.a.         |
| hot start up time       | min           | n.a.                     | n.a.         |
| ramp rate up/down       | % nom power/min | n.a.                     | n.a.         |
| specific investment     | €/kWe         | 1100–1500                |              |
| costs                   |               |                          |              |

2.2.3 Compression chillers: There are two types of chiller cycles: vapour compression and sorption. Sorption systems are thermally driven chillers; however, they are mainly used if surplus of non-expensive heat is available. Vapour compressors use reciprocating, screw or centrifugal compressors to supply the refrigerant circuit. Compressors are usually powered by electric motors, although they can also be driven by gas engines or steam turbines. Electrically driven chillers are the most popular systems to provide cold. Air-cooled compression chillers are available in sizes ranging from 0.1 to 1750 kWth and water-cooled chillers and available in sizes ranging from 21 to 21,000 kWth. Water-cooled units are more complex in installation and maintenance, but they are smaller than the air-cooled units, which require outdoor location and whose efficiency is more affected by external conditions. In addition, water-cooled units have higher full- and part-load efficiencies. Compression chillers are mature technology with no major technical barriers [19]. Nevertheless, frequent compression cycles may result in increased system wear, and temperature instability, which will lead to premature failures of the components. Short cycles may cause problems with lubrication, as there they do not let enough time for oil to circulate through the system (Table 5).

2.3 Power production

2.3.1 Steam turbines: Steam turbines are used to convert chemical energy of fuel into mechanical energy, which is used afterwards to move generators for electricity production. Power output range is up to 1900 MWe for nuclear power plants, up to 1000 MWe for coal-fired plants and up to 250 MWe for CHP units [20–22]. Steam turbines are split into three main groups: condensing, backpressure and extraction ones. Depending on the size and design of a steam turbine, different isentropic efficiencies of the turbine are achievable: 53–57% for small single-stage units, 60–67% for multi-stage units with power output <10 MWe and 75–90% for multi-stage turbines above 10 MWe. The flexibility of a steam turbine is impacted by the coupled steam generator, its combustion technology and fuel diet. Steam turbines are limited also by their cycling capability: on/off cycles are the main source of progressive deterioration of turbines material. Thermal and pressure stress applied cyclically accounts for the growth of existing flaws or incipient cracks, thus resulting in shortening the lifetime of turbine's and steam generator's components. To minimise the need for on/off operation, steam turbines should be run continuously taking into account the minimum allowed load. Therefore, their flexibility potential is mainly determined by partial load potential [23–27] (Tables 6 and 7).

Current research activities focus on the development of advanced ultra-supercritical boilers that are to produce steam with parameters around 720°C and 350 bar, thus increasing overall efficiency [28]. Besides the increase of efficiency, start up time is also expected to be shortened (1–4 h depending on starting condition) and systems should be more resistant to load change cycles and be able to provide ramping rates at a level from 10%/10 s to 10%/min. Achieving these goals will also require new plant control systems equipped with self-learning predictive systems [25].

2.3.2 Organic Rankine cycle: Electricity can also be generated by ORC systems; turbines in which blades are moved by high molecular weight hydrocarbon organic substances. Their main advantage is that organic fluids have lower boiling points and higher vapour pressures compared with water, thus offering a possibility to produce electricity from low-temperature sources. So, ORCs are widely used in applications using heat sources in the range of 70–530°C [29, 30]. ORC systems are installed either as...
primary heat-to-power technology in bio/waste-fuelled CHPs, geo-
and solar-thermal plants (up to 11 MWe of electrical output) or as a
secondary hybrid technology to recycle waste heat streams (down
to 5 kW). The gross electrical efficiency for ORC turbines is
between 5 and 26% and is highly linked with the temperature
difference between heat source and heat output. Thermal efficiency
represents the ratio between the amount of available heat output
and total energy input, and can reach up to 80%. In comparison to
steam turbines, ORC systems maintain higher partial load
efficiency and can operate down to 10–15% of their nominal load.

### Table 7 Technology factsheet – multi-stage steam turbine [12]

| Parameter                     | Unit       | Multi-stage Condensing Backpressure |
|-------------------------------|------------|-------------------------------------|
| power output                  | MWe        | 5–1900                              |
| operating temperature level   | °C         | 300–620                             |
| output                        |           | 300–565                             |
| operating temperature level   | °C         | 50–70                               |
| output                        |           | 100–400                             |
| minimum load                  | %          | 25–50                               |
| controllable range            | %          | 25/50–100                           |
| net electrical efficiency     | %          | 15–47                               |
| thermal efficiency            | %          | 0–<80                               |
| cold start up time            | min        | 240–420                             |
| hot start up time             | min        | 120–360                             |
| ramp rate up/down             | % nom power/min | 1–8%                        |
| specific investment costs     | €/kWe      | 1100–1500                           |

Start up time for an ORC system is around 20–30 min, determined
mainly by pressure and temperature stabilisation after the start up.
The ORC turbine may react to upward and downward regulation
signals from the power grid with ramp rates up to 15–30%/min, but
typical values are usually lower about 2–5% [31]. ORC units are
typically designed for only one operating point; therefore, part-load
conditions are not optimal. Frequent start ups of coupled engines
will influence temperature exhaust gases that can be used either to generate high-pressure steam, hot water or chilled water when they are coupled
with absorption chillers. Hot gases can also be used directly in industrial applications for heating or drying. The electrical generation efficiency of gas turbines varies between 25 and 62.22%
[38]; very high efficiencies are achieved for CCGTs. Nevertheless,
efficiency is highly impacted by partial load operation, declining as
the load decreases. In addition, the load affects not only the
efficiency, but also the emissions, which increase when lowering the
power output. This load is around 50–60% for CCGT heavy-
duty turbines (even if, by optimising the system, it can be reduced
to 30–40% [39]), around 25–40% for simple cycle turbines and 5–
18% for aeroderivative turbines. For hot start conditions, the start
up time for CCGT is about 30–45 min, for simple cycles it is about
10–15 min and <5 min for aeroderivative units. Ramping rates can
reach up to 6%/min for CCGT; 7.5–16.3%/min for simple cycle
gas turbines (SCTGs); and 40–132%/min for the aeroderivative
turbines [15, 40]. Furthermore, fluctuating loads and an increased
number of start ups will reduce lifetime of gas turbines; thus,
resulting in higher maintenance costs [41] (Table 9).

### Table 8 Technology factsheet – ORC [12]

| Parameter                     | Unit       | Value               |
|-------------------------------|------------|---------------------|
| power output                  | MWe        | 0.05–11             |
| operating temperature level   | °C         | 60–530              |
| input                         |           |                     |
| operating temperature level   | °C         | 60–252              |
| output                        |           |                     |
| minimum load                  | %          | 10–15               |
| controllable range            | %          | 10/15–100           |
| net electrical efficiency     | %          | 5.8–25.4            |
| thermal efficiency            | %          | s80                 |
| cold start up time            | min        | 20–30               |
| hot start up time             | min        | 15                  |
| ramp rate up/down             | % nom power/min | 15–30–2–5 (geothermal) |
| specific investment costs     | €/kWe      | 850–2300            |

### Table 9 Technology factsheet – gas engine [12]

| Parameter                     | Unit       | Value               |
|-------------------------------|------------|---------------------|
| power output                  | MWe        | 0.1–20              |
| operating temperature level   | °C         | n.a.                |
| input                         |           |                     |
| operating temperature level   | °C         | 365–465             |
| output                        |           |                     |
| minimum load                  | %          | 30                  |
| controllable range            | %          | 30–100              |
| net electrical efficiency     | %          | 29.6–42             |
| thermal efficiency            | %          | 35–53               |
| cold start up time            | min        | 10–12               |
| hot start up time             | min        | 0.5–2               |
| ramp rate up/down             | % nom power/min | 20–50 (100 for already started engines) |
| specific investment costs     | €/kWe      | 800–1450            |

2.4 Supporting technologies

### 2.4.1 Heat storage: In MESs, electricity production and consumption are often coupled with the supply of heat. The
coupled production is usually driven by customer heat needs,
which lowers the degrees of freedom for variable electricity
production. Therefore, a flexibility increase on the electricity side
requires the decoupling of the heat demand from heat supply of cogeneration and PtH units. TES enables decoupling, e.g. electricity production from CHP units can be increased if heat surplus is stored; vice versa, CHP-electricity production can be decreased if the related heat demand is covered by previously stored heat or alternative heat sources. For electricity consumption in PtH units, similar considerations arise. Thermal storage is about 100 times cheaper than electricity; so, use of TES will grow due to increasing volatile RES in the electricity mix. TES stores either warm or hot water as well as steam. Hot water tanks sizes range from some 100 dm³ for single buildings to 50,000 m³ for large DH networks. The corresponding capacities in MWh depend on the temperature differences and on the temperature levels of the entire heating system [42]. Typically, the sizing is done to provide the maximum heat demand for at least some hours to several days; resulting in a range of 30–50% of the heat peak load as the maximum heat demand for at least some hours to several days; therefore, capacities in terms of stored energy can achieve more than 2000 MWh in large DH networks [43]. TES efficiency corresponds to heat losses over time, depending mainly on the thickness of the insulation. Larger tanks are more efficient, thanks to the better surface-to-volume ratio. Mean values for the specific heat loss are around 10 W/m² or about 0.2% of capacity/day. Steam accumulators are used in industrial steam networks, usually to cover steam peak demands in batch processes, and as a back-up system instead of auxiliary boilers. In such industrial processes, steam has to be delivered with constant quality within some minutes for at least 15 min. If the dimensioning of the steam accumulator and the CHP unit producing steam is appropriate, steam storage can – similarly to hot water tanks – contribute to the decoupling of power production and steam demand. The storage capacities are usually in the range of several MWh, but new developments are broadening the capacities into the GWh range by cascading units.

3 Technical suitability and expected developments

3.1 Technical suitability to services

In the previous chapter, widely used key technologies have been characterised in terms of their flexibility. Three parameters are particularly the most important when considering flexibility provision:

- Ramp rate, expressed in units of power over time, indicates how quickly a power plant output can be adjusted up or down to meet growing or decreasing demand. Some technologies such as gas turbines are more flexible than others and serve usually as peaking units because they can be ramped up and down quickly to compensate sudden changes in supply or demand. Start up time, expressed in units of time, represents the time needed by a power plant to reach full load. A distinction is made between (i) cold start when the power plant is switched on at a low temperature relative to its normal operating temperature, (ii) hot start referring to a start occurring when the state of the plant is close to its normal operating temperature. The power output, expressed in units of power that refers to the nominal power generation. The crucial point for this parameter is the capacity size; often, the flexible capacity does not fit to the market and net provider requirements. To reach higher capacities, some power plants can be pooled together. Virtual power plants consist of a central IT control system aggregating the capacities of several homogeneous or heterogeneous distributed energy resources. This aggregation concept allows to achieve greater economy through economies of scale and reduce the complexity for market participants [44].

In Table 11, the above flexibility parameters such as power output, start up time and ramp rate of selected technologies are summarised. It can be observed that these figures vary a lot from one technology to another one and even that within the same technology class there may be large differences between minimal and maximal values (e.g. this is particularly true for SCGTs with

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\[ \text{Table 10: Technology factsheet – gas turbine [12]} \]

| Parameter       | Unit                      | Simple cycle combustion | Simple cycle aeroderivative | Combined cycle combustion |
|-----------------|---------------------------|-------------------------|-----------------------------|---------------------------|
| Power output    | MWe                       | 3–593                   | 36–117                      | 44–593                    |
| Operating temp. | °C                        | n.a.                    | n.a.                        | n.a.                      |
| Level output    |                           |                         |                             |                           |
| Operating temp. | °C                        | 365–465                 | 430–530                     | hot water or steam depending on the pressure |
| Level output    |                           |                         |                             |                           |
| Minimum load    | %                         | 25–40                   | 5–18                        | 30–60                     |
| Controllable range | %                    | 25/40–100               | 5/18–100                   | 30/60–100                 |
| Net electric efficiency | %           | 23–40                   | 32–42                      | 52–62                     |
| Thermal efficiency | %                | 44–50                   | 44–50                      | 33–38                     |
| Cold start up time | min             | 10–45                   | 10–12                      | 145–255                   |
| Hot start up time | min         | 5–15                    | 5                          | 30–45                     |
| Ramp rate up/down | % nom          | 7.5–16.3                | 82–132                     | 5.2–6                     |
| Specific investment costs | €/MWe      | 375–1130                | 960–1330                   | 545–595                   |

\[ \text{Table 11: Main technical characteristics of the considered technology [12]} \]

| Technology                        | Power output/input | Hot start up time | Cold start up time | Ramp rate % Nom power/min |
|-----------------------------------|--------------------|-------------------|--------------------|---------------------------|
| Steam turbines                    | 1–1000             | 120–360           | 240–420            | 1–8                       |
| ORC turbine                       | 0.05–11            | 15                | 20–30              | 15–30                     |
| Gas engine                        | 0.1–20             | 0.5–0.2           | 10–20              | 20–50^                   |
| Gas turbine simple cycle          | 3–593              | 5–15              | 10–45              | 8–16                      |
| Gas turbine combined cycle        | 44–593             | 30–45             | 145–255            | 6                         |
| HPC                              | 0.0005–7.5         | 3                 | 300                | 20                        |
| E-boiler                         | 0.005–60           | 0.5               | 5                  | 100                       |
| Chillers                          | 0.0002–3.2         | 3                 | 30–60              | 6                         |

\[ ^a \text{Running gas engine may have ramp rate of 100%/min} \]
\[ ^b \text{Power consumption calculated for COP} \approx 4 \]
\[ ^c \text{Power consumption calculated for COP} \approx 6.5, \text{hot start up time as for HPs.} \]
customers using electric water heaters to produce domestic hot water. These heaters are switched on at night when the energy demand response programmes [49].

Agency, European countries such as Denmark, Italy and Germany project demonstrated that electric water heaters can absorb excess major technological obstacle to the uptake of such residential 3.1.2 Power outputs: HPs, e-boilers and chillers are characterised by a small power output. These smaller units may be aggregated to form larger volumes in order to meet market entry conditions if approved by national authorities (aggregation of small size power plants is still not allowed in Spain and Italy).

The aggregation of HPs for the provision of reserve in power systems has been demonstrated in several smart grid pilots [46–48]. However, the lack of a standard for the control interface/management of demand control solutions is seen as one of the major technological obstacle to the uptake of such residential demand response programmes [49].

The flexibility provided by some smaller units is already used in some countries. German and Swiss distribution system operator (DSOs) introduced specific HP tariffs and remote control mechanism to limit the active power of these units during certain period of time when energy demand is high. As compensation, participating customers benefit from a significant reduction in network charges in their electricity bill [50, 51]. France also introduced a time of use electricity tariff especially designed for HPs/chillers and ORC systems are suited for the participation in the short-term energy balancing markets. Sector-coupling technologies with less flexible capabilities such as condensing turbines and steam turbines cannot provide the full range of flexibility services. They seem to be most relevant for intraday and day-ahead energy markets. Heat and gas storage can increase the flexibility provision of the above-mentioned technologies or local PV production, thus contributing to voltage stability in low-voltage lines characterised by high PV production and low demand [53].

3.1.3 Ramp rates: Another important feature of any generation asset in the light of flexibility procurement is its ramp rate – the rate at which a plant can decrease or increase its output to compensate fluctuations in supply and demand. According to [54], due to the increasing share of fluctuating energy sources, up to 30% of the feed-in of the national thermal generation capacities in Germany, France, Spain and Italy will need to ramp up or down by 2030. As presented in Fig. 3, simple cycle aeroderivative turbines and electric boilers are characterised by a high ramp rate. These two features make them particularly suitable for the provision of fast frequency response services. However, power plant cycling operations may lead to component damages, loss in efficiency and more operation-related emissions as well as higher operating and maintenance costs since most of the plants are designed to run as base-load plants around the clock [55]. As highlighted by [45], regulatory modifications and the introduction of economic incentives for plant operators may be needed to unlock the flexibility of thermal plants, especially the large ones.

To summarise, it appears that coupling technologies with short ramp up and start up times such as e-boilers, gas engines and simple cycle aeroderivative gas turbines meet requirements for frequency containment reserve (FCR) markets. However, e-boiler cannot provide more electricity to the grid unlike gas-based units. Simple cycle and combined cycled gas turbines and aggregated HPs/chillers and ORC systems are suited for the participation in the short-term energy balancing markets. Sector-coupling technologies with less flexible capabilities such as condensing turbines and steam turbines cannot provide the full range of flexibility services. They seem to be most relevant for intraday and day-ahead energy markets. Heat and gas storage can increase the flexibility provision of the above-mentioned technologies or system configurations to which they are coupled or in which they are integrated. It can be seen that fast ramps, and short start up times are given by small capacities; therefore, it may be necessary to aggregate them in order to provide services to the market. However, it must be noted that market rules vary from one country and the strategy to be adopted will depend largely on the local power system's condition.

Fig. 4 shows the investment cost of reactivity, which is a result of dividing specific costs of investment by ramp rates. Values vary between 0.3 for e-boilers and 375 for solid fuel steam turbines and local PV production, thus contributing to voltage stability in low-voltage lines characterised by high PV production and low demand [53].
compared with another technology, for which the flexibility of the electricity system, but also minimises operational costs and/or environmental costs, maintenance, electricity costs etc. Hybridisation, e.g. coupling gas engines with e-boilers, may not only increase the capability of the MES to provide flexibility to the electricity system, but also minimise the operational costs and/or increase the incomes. From a technology coupling perspective, thermal storage is necessary: even though it does not directly provide flexibility to the electricity markets, it enables to decouple electricity and heat production, which is important to maintain high overall efficiency.

3.2 Major trends and expected developments of the energy system in the European Union

The energy system and power, heat and gas markets undergo a transformation driven by rapid growth of renewables, higher-energy efficiency, thanks to more stringent regulations, digitalisation and electrification in the cooling, heating and transport sectors. The major trends and developments identified in the EU reference scenario 2016 with projections until 2030 for the selected sector-coupling technologies are as detailed in the following paragraphs [56].

A moderate increase in efficiency, combined with a decrease in costs, can, however, be assumed for all considered technologies. However, as stated in [57], the decentralisation of power generation from RES, sector coupling and digitalisation increasingly expose the energy system to cyberattacks and incidents, which may jeopardise the security of energy supply.

Energy network operators and relevant stakeholders will have then to make sure to follow the available recommendations on real-time requirements, cascading effects and combination of legacy and state-of-the-art technology to reduce and control the cybersecurity risks. These include, for example: splitting the overall systems into logical zones to enable the application of suitable cybersecurity measures, establish design criteria and an architecture for a resilient grid and establish an automated monitoring and analysis capability for security-related events.

3.2.1 Power-to-heat: The steam and heat demand in the EU28 is expected to remain approximately stable throughout the projection period. In the long-term, e-boilers and HPs penetrate the DH market and increase their market share while solid and gaseous fuels see their share reduced. For HPs and refrigeration units, the biggest challenge is the upcoming ban on the use of fluorinated gases (F-gases) as refrigerants. The use of environmentally friendly alternatives may affect performance and the cost of future deployed technologies. Regarding electric boilers, it is expected that sales of small heaters (also called ‘boosters’) will increase because the use of an additional energy source (electricity) is often needed for domestic hot water preparation in low-temperature DH networks and heating systems [58]. Furthermore, high-temperature HPs are likely to increase in importance in the future because their potential contribution to efficiency improvement of base-load CHP plant connected to DH networks and can be used to produce steam at local consumption point for industrial processes instead of fossil fuels [59]. Generally speaking, it can be said that steam will be produced more and more by PtH technologies, but also from natural gas and biofuels, and less from other fossil energy sources.

3.2.2 Power-to-cold: The demand for air conditioning will increase because cooling degree days are assumed to augment. Thus, more chillers will be rolled out in the residential sector. These small units can be aggregated to collectively address grid issues [60]. According to Pezzuto et al. [61], space cooling is responsible for a significant portion of EU electricity consumption in households (∼5%) and in the tertiary sector (∼13%). This market is characterised by a strong growth potential, particularly in households.

3.2.3 Heat-to-power: The conversion of heat to electricity via ORC systems is gaining in importance. Especially, waste to heat recovery is an emerging field for ORC with an interesting potential for all unit sizes ranging from medium- to large-sized plants recovering heat from gas turbines, internal combustion engines or industrial processes [62]. From a technological point of view, the development of high-temperature materials is necessary to recover heat from sources with increasingly high temperatures. Similarly to HPs, ORC systems can improve the efficiency of the PtH technologies to which they are coupled, resulting in a very load-flexible power plant with optimal part-load efficiency and compliance with emission standards.

3.2.4 Gas-to-power: Gas-fired generation slightly increases due to the role that gas is playing as a back-up technology for intermittent renewable sources. The majority of investments are in CCGT plants used for flexibility and reserves. The share of CHP (mainly fuelled with gas and biomass) will increase following the general trend toward highly efficient power plants. It is also expected that the global gas engine market will grow, especially for the units sized between 400 kW and 20 MWe. Key drivers for this development are falling on low oil and gas prices and ambitious renewable energy targets [63].

Besides that, due to very high electrical (up to 60%) and overall efficiency (up to 85–95%) fuel-cell-based cogeneration may play a big role in the future CHP systems [64–66].

Fig. 5 shows that the global installed capacity of fuel cells has increased more than ten times in recent years. In the US, some
units have a capacity up to 6 MWe and are used in commercial buildings [67]; South Korea is becoming a key player for fuel cells deployment with the biggest fuel-based CHPs in the world [68, 69]. On the other hand, Japan is very active when it comes to micro-CHPs what is proven by almost 300,000 already installed residential units [66]. Nevertheless, further R&D are still required to deal with some technical challenges to lower down the investment costs and increase their lifetime and flexibility [70]. Besides natural gas, they can be fuelled both with hydrogen and biogas, which may help to decarbonise the heat and power production.

3.2.5 Heat storage: The EU Reference Scenario does not take into account supporting technologies such as heat and gas storages. However, it can be assumed that hot water tanks and steam accumulators will play a key role to compensate daily, weekly and seasonal fluctuations in heat demand, as well as a more flexible CHP performance. Combined with other coupling technologies such as e-boilers, heat storages can provide additional flexibility to the power system and support the integration of renewable energy resources. New steam storage systems are expected to offer significant cost and performance benefits. (Bio-)gas storages will remain a niche market that will mainly serve to exploit flexibility in industrial sites, where gas production or demand is important.

4 Conclusion

As presented in this paper, sector-coupling technologies, which are becoming increasingly more and more important due to the penetration of distributed resources and digital transformation can provide flexibility to the power system. An analysis carried out for selected technologies shows that their capabilities to provide system services are mainly dependent on technical flexibility features such as power output, ramp rate and hot/cold start time, which has also to fit and to the characteristics of the flexibility products (minimum volume and eligible technologies) that may differ a lot from one country to another. In particular, gas-fuelled units (e.g. turbines and engines) appear to be the most promising solutions for flexibility provision, thanks to their technological characteristics, modularity and cost-effectiveness. Thermal systems can be supported on the other hand by electric boilers and heat storage, for effectively decouple heat demand and production, while maintaining high production efficiency. Thanks to the development in terms of lifetime and costs, fuel cells are expected to become a reliable solution for small-scale cogeneration in the next decade.

However, not only technical factors are vital for the provision of flexibility services, but also the economic ones. According to [45], many existing generators are inflexible from an economic standpoint of view because of must-run requirements and performance-based regulations. The steps to be taken to unleash the flexibility potential of sector-coupling technologies are strongly dependent on local grid conditions. Nevertheless, there are some general guidelines to follow to enhance power system's flexibility. First, it is crucial to assess accurately and regularly the flexibility requirements of a given country or balancing area and determine the flexibility potential that can be provided by specific coupling technologies. In a second step, policy actions such as the revision of inflexible contract terms, the development of innovative market design and the creation of fair compensation for flexibility provision will be required. The Horizon 2020 MAGNITUDE project that aims at developing business and market mechanisms, as well as supporting coordination tools to provide flexibility to the European electricity system will help tackle some of these challenges.

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6 References

[1] Committee of Climate Change ‘Roadmap for flexibility services to 2030’, 2017. Available at https://www.theccc.org.uk/wp-content/uploads/2017/06/Roadmap-for-flexibility-services-to-2030-Poetry-and-Imperial-College-London.pdf, accessed on June 2019

[2] ‘Electricity and heat statistics,’ © European Union, 1995-2013. Available at https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_and_heat_statistics, accessed June 2019

[3] Schmidla, T., Stadler, I.: ‘Prospective integration of renewable energies with high capacities using combined heat and power plants (CHP) with thermal storages’, Energy Procedia, 2019, 99, pp. 292-297. Available at https://doi.org/10.1016/j.egypro.2016.10.119, accessed on June 2019

[4] Climate Policy Initiative: ‘Flexibility – the path to low-carbon, low-cost electricity grids’, 2017. Available at https://climatepolicyinitiative.org/wp-content/uploads/2017/04/CI-Flexibility-the-path-to-low-carbon-low-cost-grids-April-2017.pdf, accessed on June 2019

[5] Cauret, L., Belhomme, R., Renou-Desfossez, P., et al.: ‘Benchmark of markets and regulations for electricity, gas and heat and overview of flexibility services to the electricity grid’, 2019. MAGNITUDE project deliverable, available at https://www.magnitude-project.eu/wp-content/uploads/2019/07/MAGNITUDE_D3_1_Final_Submitted.pdf

[6] International Energy Agency: ‘Linking heat and electricity systems- Co-generation and district heating and cooling solutions for a clean energy future’, 2014. Available at https://www.iea.org/publications/freePublications/publication/LinkingHeatandElectricitySystems.pdf, accessed on June 2019

[7] Rinne, S., Syri, S.: ‘The possibilities of combined heat and power production balancing large amounts of wind power in Finland’, Energy, 2015, 82, pp. 1034-1046. Available at https://doi.org/10.1016/j.energy.2015.02.002, accessed on June 2019

[8] Connolly, D., Lund, H., Mathiesen, B.V., et al.: ‘Heat roadmap Europe: combining district heating with heat savings to decarbonise the EU energy system’, Energy Policy, 2014, 65, pp. 475-489. Available at https://doi.org/10.1016/j.enpol.2013.10.035, accessed on June 2019

[9] Korpela, T., Kaivosoja, J., Majanne, Y., et al.: ‘Utilization of district heating networks to provide flexibility in CHP production’, Energy Procedia, 2017, 116, pp. 310-319. Available at https://doi.org/10.1016/j.egypro.2017.05.077, accessed on June 2019

[10] Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. Brussels: European Council. 14 November 2012. Available at https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:315:0001:0056:en:PDF, accessed November 2019

[11] Eurostat, Final CHP reporting instructions Eurostat for the reference year 2016. Available at https://ec.europa.eu/eurostat/documents/38154/424195/ Final_CHP_reporting_instructions_reference_year_2016_onwards_30052017.pdf?sfvrsn=ae3-499b-hf3-88f998840ffe8, accessed on June 2019, accessed November 2019

[12] Horizon 2020 Magnitude project: ‘D1.2 – Technology and case studies factsheets, 2019

[13] VDE - Verband der Elektrotechnik Elektronik Informationstechnik e.V.: ‘Potenziale für Strom im Wärmenmarkt bis 2050’, 2015
[64] Fuel cells. Available at https://hydrogeneurope.eu/fuel-cells, accessed November 2019

[65] DOE, U.S. ‘Fuel cell technologies office’. Available at https://www.energy.gov/sites/prod/files/2015/11/fcto_fuel_cells_fact_sheet.pdf, accessed November 2019

[66] Arias, J.: ‘Hydrogen and fuel cells in Japan’, EU-Japan Centre for Industrial Cooperation, Tokyo 2019. Available at https://www.eu-japan.eu/sites/default/files/publications/docs/hydrogen_and_fuel_cells_in_japan.pdf, accessed on June 2019

[67] DOE, U.S. ‘Combined heat and power installation database’. Available at https://doe.icfwebservices.com/chpdb/, accessed November 2019

[68] South Korea’s ambitious plans for fuel cell CHP capacity. Available at https://www.powerengineeringint.com/2012/07/01/south-koreas-ambitious-plans-for-fuel-cell-chp-capacity/, accessed November 2019

[69] South Korea: Work Begins on World’s Largest Hydrogen Fuel Cell Power Plant. Available at https://fuelcellsworks.com/news/south-korea-work-begins-on-worlds-largest-hydrogen-fuel-cell-power-plant-commissioned/, accessed November 2019

[70] Technology Data - Energy Plants for Electricity and District heating generation, The Danish Energy Agency. Available at https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_el_and_dh.pdf, accessed November 2019

[71] Weidner, E., Ortiz Cebolla, R., Davies, J.: ‘Global deployment of large capacity stationary fuel cells – drivers of, and barriers to, stationary fuel cell deployment, EUR 29693 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-00841-5, doi:10.2760/372263, JRC115923