

# Flexibility provision through enhanced synergies between electricity, gas and heat systems: a comparative analysis of market and regulatory frameworks in seven case study countries

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Lionel Cauret<sup>1</sup> ✉, Regine Belhomme<sup>1</sup>, Pauline Raux-Defossez<sup>2</sup>, Stanislas Nösperger<sup>3</sup>, Johannes Steinbeisser<sup>4</sup>, Juana Pagán Carpe<sup>4</sup>

<sup>1</sup>EDF, Research & Development, Palaiseau, France

<sup>2</sup>EfER Europäisches Institut für Energieforschung, Karlsruhe, Germany

<sup>3</sup>Efficacy, Champs-sur-Marne, France

<sup>4</sup>Regenera Levante S.L., Murcia, Spain

✉ E-mail: lionel.cauret@edf.fr

**Abstract:** With the increased share of renewable energy sources, there is a growing need for more flexibility to ensure the efficient and reliable operation of the electricity system. Multi-energy systems (MES) now appear as one possible means to provide such flexibility through increased synergies between electricity, gas, and heating/cooling systems. In this context, the main findings of the study carried out in the MAGNITUDE European project are described. The most relevant services that could be provided by MES to the electricity system are first presented. Then a methodology is proposed to characterise and compare the market organisations and mechanisms for their procurement. The results of its application in seven case study countries are summarised and illustrate the diversity met between countries. The gas and heat sectors are also investigated for the seven countries to characterise the main aspects relevant to the provision of the services by MES. A comparative analysis is then carried out between the three energy sectors in the seven countries and highlights the major similarities and differences. Finally, potential barriers for the provision of the services by MES are discussed regarding the market, regulatory, and cultural aspects.

## 1 Introduction

The European targets for renewable energy integration, reduction of greenhouse gas emissions, and energy efficiency require important changes in the energy system. With the increased share of renewable energy sources (RES), the electricity system is expected to be exposed to new or increased risks for instance in terms of security of the electricity supply, congestion, system stability, and difficulty to meet the demand at some periods of time.

To face this evolution, there is a growing need for more flexibility to ensure the efficient and reliable operation of the electricity system. Different flexibility resources are emerging: electric storage, demand-side response, automation and sensor technologies etc. Among them, increased synergies between different energy carriers appear now as one possible means to provide such flexibility.

### 1.1 Literature review

These synergies between electricity, gas and heating/cooling systems already exist, such as combined heat and power (CHP) units, heat pumps (HPs), power-to-gas, gas-to-power, power-to-heat etc. MESs characterisation and modelling have been highly studied from a technical point of view. For instance, Bloess *et al.* [1] provide a review of technologies for power-to-heat; Gabrielli *et al.* [2] propose an optimal design of MES with seasonal storage; Zheng *et al.* [3] analyse a new integrated heat and power dispatch model considering the thermal inertia of a district heating (DH) system; Mancarella [4] presents MES concepts and a critical discussion on the performance metrics that have been proposed to capture costs and benefits; Mancarella *et al.* [5] highlights challenges and opportunities of MES modelling.

The assessment of the MES technical potential is another key issue, as shown by Schweiger *et al.* [6] focusing on the potential of power-to-heat in Swedish DH systems and by Yilmaz *et al.* [7] assessing the MES potential in Europe.

Activities to promote cross-sectorial integration can also be mentioned, for instance, those carried out by the ERA-Net Smart Energy Systems community [8].

Beside the technical perspective and MES modelling, market designs and regulatory frameworks appear as another decisive issue: the development of MES flexibility services to the power system will also depend on their ability to respond to the power system's needs, i.e. their ability to participate in existing and future service procurement mechanisms.

As pointed out in [9], the electricity, gas, and heat markets currently remain decoupled, independent from one another and largely dissimilar. The provision of services by MES to the power system raises the need for a certain level of coupling or, at least, coordination between power, gas, and heat market designs and regulatory schemes. For this purpose, Kessels *et al.* [9] propose five innovative multi-carriers market schemes with different levels of integration. An inter-disciplinary approach – technical, economic, and social – is presented in [5] as the key underlying challenge in MES research. Also, Zhong *et al.* [10] study a local platform for auction mechanisms to trade electricity, heat, and gas in a smart multi-energy district. The strategic behaviour of multi-energy participants in electricity markets is also addressed, as explained by Yazdani-Damavandi *et al.* [11].

A focus on regulatory and economic barriers or facilitators is crucial to qualify the MES's ability to provide flexibility services. Numerous surveys propose a particular focus on the Nordic countries where heating networks are already highly developed: Skytte *et al.* [12] identify several types of regulatory and market barriers which lower the potential use of DH as a source of

flexibility for the Scandinavian electricity system; the authors of [13, 14] focus on the electricity grid tariff structure in the Nordic countries as a facilitator or a barrier to couple DH systems to the electricity one and to activate flexibility from power-to-heat technologies. The Flex4RES project can also be mentioned with its objective to more coupled energy markets across the Nordic region [15, 16]. Other surveys give a pan-European overview, such as [7], which concludes that the power-to-heat potential significantly depends on the national energy system considered.

The understanding of the power system needs of the associated services procurement schemes and their evolution is another major issue. Some synthetic surveys such as [17, 18] present a global comparison of existing services procurement to the power system in Europe. Others propose a more detailed comparison and recommendations to adapt existing mechanisms – or to set up new ones – dedicated to specific flexibility resources: SmartNet [19] analyses the potential of ancillary services provided by distributed generation and demand side management; Smart Energy Demand Coalition (SEDC) [20] analyses the regulatory framework conditions in 18 European countries for explicit demand response (i.e. aggregated demand-side resources directly competing with other resources in the existing mechanisms); EU-SysFlex [21, 22] explores innovative system services and possible market organisations for operating the power system with a large development of RES; in its literature review of market designs, Hu *et al.* [23] conclude that an electricity market overhaul is needed in Europe to overcome existing market barriers to the large-scale integration of variable renewable electricity. National works can complement these comparative analyses such as the British roadmap for flexibility services [24].

## 1.2 Contribution

The main findings of a study carried out in the MAGNITUDE H2020 European project [25] are described. The scope is the identification of the most relevant flexibility services that can be provided by MES to the electricity system to support the integration of RES, and the comparative analysis of the market and regulatory frameworks for their provision in seven case study countries, i.e. the characterisation and comparative analysis of the existing procurement mechanisms in these countries [26]. The considered countries are Austria, Denmark, France, Italy, Spain, Sweden, and Great Britain (GB). They are the countries where the seven real-life case studies of MES studied in the MAGNITUDE project are located.

The gas and heat sectors are also analysed for the seven countries to characterise the main aspects relevant to the provision of the identified services by MES. A comparative analysis is then carried out between the three energy sectors in the seven countries and highlights the major similarities and differences. Finally, various types of the potential market and regulatory barriers to the provision of the flexibility services by MES are finally discussed.

The results presented in this study are then used in the next phases of the project, for instance for the assessment of the flexibility provision capability of cross-sector technologies and MES, the development and modelling of innovative market

designs, the modelling and optimisation of MES, and the provision of services through the aggregation of MES. The results of these phases are out of the scope of the present paper and will be the subjects of separate publications (e.g. technical characteristics of case studies [27, 28], evaluations of future market designs for MES to procure flexibility [9, 29], multi-energy market simulator [30] etc.).

The paper is organised as follows. The relevant services that were identified are first presented in Section 2 and the main characteristics of the electricity system and associated service procurement mechanisms are given in Section 3. Sections 4 and 5 provide the main characteristics of the gas and heating/cooling systems. A comparative analysis of the three sectors is then given in Section 6 and potential barriers for the provision of the services by MES are discussed in Section 7.

## 2 Selection of relevant services

### 2.1 Identification of relevant services to be provided by MES

First, the main needs of the electricity system have been considered, based on a literature review, including in particular legal and regulation texts, such as transmission system operator (TSO) documents and network codes. They can be differentiated in three main categories:

- The needs of the system operators to ensure the physical match between supply and demand.
- The needs for the states/policy makers and for the TSO to guarantee the system adequacy.
- The needs of energy sellers and buyers to trade energy.

Services are procured to meet these needs. Among these services, the most relevant ones for the MAGNITUDE project's goals have been selected using the following criteria, namely services:

- that allows us to increase the share of RES and enhance the security of supply,
- for which enhancement of synergies between electricity, heating/cooling, and gas systems provide real opportunities,
- for which first elements (technical, regulatory, market design) show a potential value for the provision by MES.

The resulting list is given in Table 1.

It should be noted that in the electricity system, the enhancement of the synergies between electricity, gas, and heating/cooling systems mainly has an impact on ‘energy’ or active power. Therefore, the most relevant services are indeed those services linked to active power.

For this reason, voltage control as such does not appear in Table 1. Indeed, in most cases, voltage control is a mandatory service being carried out by acting on reactive power at the connection point and thus it depends on the reactive power control capabilities of the equipment connected to the grid. However, on the distribution networks, due to the technical characteristics of the medium voltage (MV) and low voltage (LV) lines, active and

**Table 1** Selected electricity system needs and services

Needs	Services
frequency control and balancing	FCR aFRR mFRR and RR dedicated additional balancing mechanisms which may exist in certain countries
energy trades	day ahead energy trades/market intraday energy trades/market
system adequacy	capacity requirement mechanisms
congestion management at transmission and distribution levels	re-dispatching mechanisms or active power control

reactive powers are much more ‘coupled’ than on the transmission networks, and active power control or re-dispatching can also be used to control the voltage at MV or LV levels, in combination with the management of power flow constraints. Therefore active power control or re-dispatching is a flexibility service that could be offered to the distribution system operator (DSO) to meet its needs both in terms of power flow management and voltage control.

Other services do exist but are not considered in this study since they appear less relevant with respect to our scope, for instance:

- Power quality management is often a mandatory service that will probably not be remunerated and will not benefit from synergies between energy carriers.
- The minimisation of grid losses is also not considered since its remuneration is very uncertain.
- The potential value from the participation of MES to system restoration is expected to be rather low and cannot be easily assessed.

Since the focus is on the existing service procurement mechanisms in the seven case study countries, we do not consider the future services which are currently under investigation but not implemented yet in the considered countries such as ramping, merging or inertial response [19, 31, 32]. Further research will be required on the characteristics of the products and the design of the new market mechanisms and remuneration schemes.

In order to further assess the potential development of the selected service provision by MES and to identify potential barriers and facilitators, it is then necessary to

1. Have in-depth knowledge of the design of each relevant service procurement mechanism required by each national power system.
2. Describe the main characteristics and constraints for each of the three energy systems.
3. Carry out a ‘symmetric’ comparison of the three energy systems in the seven countries considered in the MAGNITUDE project.

## 2.2 Key parameters for relevant services

The mechanism for the provision of service generally consists of the same global three-step process:

1. The planning and product procurement phase, sometimes years before the service delivery period: it includes the identification of the needs by the service buyer (TSO, DSO) or another type of player depending on the service), the formulation and submission of requests and/or bids, market clearing or over-the-counter (OTC) negotiation, contract conclusion, testing process, certification of the provider in some cases etc.
2. The delivery phase itself: it includes activation mechanisms depending on the service, the physical delivery of the products, real-time monitoring, measurement/metering etc.
3. The settlement or post-delivery phase, including exchanges of metered data, financial settlement, remuneration and possible penalties in case of failure to deliver the contracted product.

Although the basic needs of the electricity systems are the same across Europe, the designs of the electricity markets are currently not harmonised at European level, as a consequence of former or recent particularities, such as composition of the generation mix, location of demand and generation, network typology, insular or continental system, population density, development of electrified thermal end-uses etc. Each national combination of these particularities may then amplify some power system constraints, inducing an adapted and country-specific range of mechanisms to solve them.

In order to benchmark the services in different countries, the following parameters have been analysed and compared:

- Type of mechanism (centralised/decentralised, auction-based or not, etc.).

- Types of players involved.
- Eligible technologies (e.g. generation, demand, and storage).
- Eligibility of aggregation. (Is a demand or generation aggregation eligible?)
- Type of participation (mandatory or not).
- Volume thresholds (minimum and maximum bid volumes, minimum bid increment).
- Types of products and their characteristics, such as lead time, ramping or slopes, deployment or activation duration, duration between two activations, number of activations per period, and other specific features.
- Type of selection (hourly/daily/weekly/monthly process? Bilateral?)
- Type of remuneration (pay-as-clear, pay-as-bid, no remuneration etc.)

An example of the automatic frequency restoration reserve (aFRR) is given in Section 3.4.

## 3 Main characteristics of the electricity system

### 3.1 Main needs, constraints, and particularities

Supply and demand of electricity continuously change. Also, the electricity storability – dams, pumping stations, thermal storage – presently remains relatively limited.

The system operators are then obliged to implement complex real-time management of the power system to ensure the permanent physical match between supply and demand (i.e. balancing) and to maintain the system/network operational parameters within their optimal range (voltage, frequency, power flows, congestions etc.). In addition, the system operators continuously prepare appropriate measures to be taken to avoid any risk of blackout and to restore the system if such an event would happen.

On their side, producers and generation aggregators need to sell their production while suppliers, demand aggregators, and large customers need to buy electricity to cover their demand. These energy transactions are necessary but create risks for the players (risk of price fluctuations, risk of volume, counterparty risk etc.): each market player is then obliged to adopt its own hedging strategy. The full or partial vertical integration of generation and supply is another way to limit these market risks.

Eventually, the security of supply remains the energy top priority for each state. However, in some countries, the adequacy of the future power system can appear uncertain in the current context. Such states are then inclined to implement particular schemes to motivate investors and to ensure that the national forecasted future generation mix in one or several years from now will indeed be able to meet the forecasted global demand, according to the targets they have defined.

### 3.2 Geographical scales

The product ‘electricity’ is considered as a universal service: that implies notably a geographical coverage of the whole national territory and the continuity of service.

Contrary to gas and heat networks, the power grid is then developed everywhere and it has meshed at the regional, national, and supra-national scales to guarantee system security.

### 3.3 Types of markets

Three main categories of the market presently exist to fulfil the above needs.

The energy markets aim to limit the risks of the players such as producers, aggregators, suppliers, and large industrial consumers (notably price and volume risks). They are organised in competitive schemes as centralised platforms (electricity exchanges) or as decentralised transactions (bilateral contracts or OTC deals). They cover a large panel of time horizons: from three-year-ahead to day-ahead (or spot), as well as intraday transactions usually until 45 min before the real-time. The forward markets

notably permit to cover the risk of price fluctuations while the spot market and the intraday transactions permit to cover the risk of volume. The forward and intraday markets are based on continuous quotations with a pay-as-bid principle while the spot market uses day-ahead auctions generally with an hourly pay-as-clear resolution (hourly and half-hourly resolution in GB, hourly and 15-min resolution in Austria). Let us note that the day-ahead market is crucial: it fixes an energy price for each hour of the following day which is also used as a reference price by a lot of other power schemes.

Among the energy markets, the retail market is specific as the place where the final consumer chooses among the offers of competing suppliers to be supplied. It remains highly monitored by each national regulator, particularly to maintain a fair competition and to protect the small end consumer (actions against fuel poverty; continuous measures against the barriers met by the consumers to switch supplier; fair competition between regulated tariffs and free retail offers in France [33]; instauration of temporary price caps on prepayment offers in 2017 and on default energy tariffs in 2019 in the United Kingdom [34] etc.). The retail market is changing constantly with the roll-out of smart meters, the development of dynamic pricing, self-consumption etc. For instance, new channels for electricity sales via peer-to-peer platforms have been emerging for several years now: such a peer-to-peer electricity trading – or any other forms of local energy market – allow for instance a grid-connected end customer to directly choose a local green producer and negotiate with him/her regarding prices, freeing the customer at least partially from traditional suppliers.

Flexibility services can be procured on the retail market, e.g. via demand–response programmes implemented by suppliers or aggregators. In this case, the provision of flexibility to the electricity system is not direct, namely, the flexibility of the final consumers is first provided to the supplier and/or aggregator, which will then use it in the bid they make on the wholesale energy markets, balancing markets or capacity requirement mechanisms.

Balancing markets are managed by TSOs to guarantee the security of the power system. Two different aspects or phases must be distinguished: (i) the procurement of power reserves in order to guarantee the availability of flexible resources when they will be needed; and (ii) the activation of the successive reserves (frequency containment reserve (FCR), aFRR, manual frequency restoration reserve (mFRR) etc.) and the actual energy delivery, in case of frequency deviation to continuously guarantee the physical balance between supply and demand.

Capacity requirement mechanisms exist only in some countries. They permit to cover the risks associated with future system adequacy identified by these states. They imply the remuneration of available capacity (€/kW) to provide energy during particular peak periods of the relevant delivery years. They are accepted by the European Commission (EC) under certain conditions and as temporary mechanisms [35]. Note that capacity requirement mechanisms based on auctions are relatively recent (first capacity auctions in December 2014 in the GB).

### 3.4 Degree of similarity between the considered countries

Several structural elements from the past explain some remaining differences: different ‘historic’ electricity mix, various policies to develop RES, different voltage thresholds between distribution and transmission networks, level of local authorities’ involvement in energy and power of decision etc.

The design of the energy markets is already highly similar in European countries, i.e. particularly true for the national spot markets, permitting a market coupling for most of the countries (i.e. the same spot price when interconnections are not saturated).

In the seven studied countries, trading on the day-ahead energy market is anonymous and takes place during daily auctions. Participation is voluntary and open to producers, suppliers, large consumers, traders, and brokers. All countries require bids with a minimum volume increment of 0.1 MW. Hourly (1 h) products are traded for the following day. There are, however, some national specificities regarding the design of the products, for instance, the

possibility to trade half-hourly products in GB or 15-min products in Austria [36].

Additionally, 14 national intraday markets are also coupled since June 2018 via a cross-border intraday platform: this coupling is expected to be enlarged to seven other countries at the end of 2019.

Concerning electricity system operation, the types of constraints faced by all national power systems are common but the national schemes developed and implemented to overcome them remain highly different. In fact, the hierarchy between system constraints differs notably because of the respective network particularities, the energy mix, and its dynamics. For instance, this is the case for the balancing systems (self-dispatch model for most European countries or centralised dispatch model in Italy, Greece, Hungary, Ireland, and Poland [37]; reactive model to manage imbalances in real time or proactive model to manage forecasted imbalances in advance [38, 39]) and the management of congestions [40].

More specifically, the design of the balancing markets varies widely according to the country studied. As mentioned above, in Italy, the balancing model used by the system operator is a highly centralised type whereas, in France, GB, Spain, Denmark, and Sweden, the type is rather intermediate with self-dispatch system operation, a centralised balancing, and a proactive model. The same configuration applies in Austria with the difference that the model is rather reactive, meaning that the imbalances are solved in real-time [19].

The aFRR also illustrates the diversity of designs within the case study countries. The objective of the aFRR service is to provide an active power reserve that is automatically activated to replace the FCR after a frequency deviation and to restore the frequency to its nominal value.

National aFRR mechanisms still show significant differences throughout Europe, in particular, due to the different generation structures from one country to another, as shown notably by ENTSO-E [17, 18] and SEDC [20]. Here are a few examples

- The frequency restoration reserve is sized by the TSO in charge of a given geographical area. Each TSO is then free to fix the repartition between aFRR and mFRR. As a consequence, the way to use the aFRR to balance a national system significantly varies from one country to another. According to the estimates of ENTSO-E [41] on the share of the activated aFRR balancing energy in 2015, this ratio was below 20% in Denmark and Sweden, between 20–40% in Italy and Spain, between 40–60% in France and beyond 80% in Austria. In absolute terms, aFRR volumes vary in average from 100 MW in Denmark to 650 MW in France and around 600 and 700 MW in Spain.
- The participation of the aFRR scheme is either voluntary (e.g. Austria, Denmark, and Spain) or mandatory (e.g. France and Italy).
- Aggregation of loads and generation is accepted in Austria, Denmark, France (if connected to the transmission network) and in Sweden, but not yet in Italy and Spain.
- The minimum authorised offers vary from 1 MW (Denmark and France) to 5 MW (Austria and Sweden).
- The requested full activation time (FAT) also varies from one country to another: <5 min in Austria and Italy; <120 s in Spain and Sweden; <400 s in France. In the case of Denmark, the power system is organised in two zones: the Western-DK1, which is synchronous with Germany and the continental grid, and the Eastern-DK2, which is coupled with the Nordic grid. As a consequence, there are two different FATs: <5 min in the DK2 zone and <15 min in the DK1 zone [42].

Another example of diversity is given in Table 2 for the ramping time requirements of FCR.

Nevertheless, the efforts of the European Union (EU) and TSOs to harmonise the rules are effective. For instance, in late 2017, the EU defined a plan aiming to harmonise the national balancing systems within 2023 (EU Guideline on Electricity Balancing) [37].

Regarding aFRR, eight TSOs from five countries (APG, Elia, TenneT NL, RTE, 50Hertz, Amprion, TenneT DE and TransnetBW) took the initiative in 2017 to anticipate such

harmonisation development via their PICASSO Project (Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation) [43]. An explanatory document was published in November 2018 by all the TSOs with their proposals [44]. Some examples of proposed evolutions are no harmonisation of FAT at go-live of the platform until 18 December 2025, then a harmonised FAT of 5 min; minimum bid size equal to 1 MW, with a bid granularity of 1 MW etc.

Similar initiatives managed by some TSOs to achieve harmonisation were launched and are on-going for FCR cooperation initiative and restoration reserves [MARI Project for mFRR and TERRE Project for replacement reserve (RR)].

Finally, the capacity requirement mechanisms – when existing like in France or in the UK – may take very different forms depending on the country: strategic reserve, targeted capacity payments or capacity mechanisms [35]. Aggregation might be allowed, in France below 100 MW, in the UK under certain conditions. The evolution of such mechanisms remains closely monitored by the EC.

### 3.5 Resources of flexibility

Resources of flexibility have been used for a long time in the electricity sector: for instance flexibility of dispatchable production; adaptation of the industrial demand; energy storage via hydropower plants (dams, pumped hydro power plants), thermal storage (e.g. water heaters with big tanks); networks as facilitators (e.g. connection between territories).

However, new flexibility resources are now emerging: for instance the flexibility of distributed energy resources such as distributed generation, demand response, battery energy storage etc. Also, MESs appear as one of these new potential options. The authors of [45–47] show that as the combination of an electric HP and a fossil-fuelled boiler under an optimised control strategy, the different configurations of hybrid HPs – add-on HP, integrated HP or packaged HP – can also present interesting flexible characteristics for the power system during load peaks.

## 4 Main characteristics of the gas system

### 4.1 Main needs, constraints, and particularities

The product ‘natural gas’ is used for heating, hot water, cooking, industrial processes etc. It can be transported via a network of pipes or in containers and barrels.

Natural gas is subject to various chemical and physical requirements to ensure the quality and security of the gas that

arrives at the consumer's premises. Operational restrictions and balancing mechanisms are also in place to ensure the security of supply when gas injection or withdrawal actions are undertaken. The pressure in the gas pipes is a key parameter that must be maintained between critical values: it is already a stake in the power sector due to the generation by gas-fired plants. Specific restrictions also ensure security and safety due to the flammable nature of natural gas.

Storability of natural gas is relatively easy. It includes the volume of gas stored in the transmission and distribution pipelines or line pack. It can also be achieved in liquid or gaseous form in over-ground storage facilities or underground reservoirs with storage ability depending on their type (volume capacity, speed to re-inject gas etc.).

Gas storage facilities permit to manage the gas system constraints [48] such as seasonal and short-term balancing and the management of the gas emergency situation.

Non-discriminatory access to the existing storage capacities appears as a decisive element: (i) presently to push competition and (ii) in the future, to enable the RES storage via power-to-gas facilities [49]. Let us add that the gas networks can be considered as an intermediate storage system (pipe gas) within the limit fixed by pressure constraints.

### 4.2 Geographical scales

Natural gas is not considered a universal product, i.e. there is no obligation to deliver gas in the whole country. For this reason, gas networks may not be present in some regions of a country. In these cases, if natural gas is demanded, it has to be delivered in liquid form in barrels.

In case there is a natural gas network, gas is transported via pipelines in the higher pressure (~16–100 bar) transmission network over long distances and then in the lower pressure (~1–25 bar) distribution networks over shorter distances to the consumers' premises. Natural gas may also be transported in liquid form in barrels to various entry points of the pipeline network.

### 4.3 Types of markets

The wholesale gas market consists of transactions between natural gas producers and suppliers and gas distributors. In recent years, a gradual liberalisation of the market is implemented in the EU. However, many gas trading hubs are not yet mature and well established [50]. Besides OTC trading, organised markets are in place via platforms such as PEGAS/POWERNEXT.

**Table 2** Ramping requirements in the FCR mechanism in the seven case study countries (based on [26])

Countries	FCR ramping times
Austria (AT)	50% in 15 s and 100% within 30 s
Denmark (DK)	zone DK1: within 30 s zone DK2: – FCR-N: 100% within 150 s – FCR-D: 50% within 5 s and 100% within 30 s
France (FR)	50% within 15 s and 100% within 30 s
Italy (IT)	50% within 15 s and 100% within 50 s
Spain (ES)	depending on the imbalances volumes. If >1500 MW, 50% within 15 s and 100% within 30 s if <1500 MW, within 15 s
Sweden (SE)	FCR-N: 63% in 60 s, 100% in 3 min FCR-D: 50% within 5 s, 100% within 30 s
UK	100% between 1 and 30 s

Note: In Denmark and Sweden, two types are distinguished: FCR-N for the normal operating band (with 49.90 Hz <  $f$  < 50.10 Hz) and FCR-D for larger frequency deviations (below 49.90 Hz).

Like for electricity, the retail gas market comprises transactions between retailers and final consumers. The intention of the EC is to liberalise the retail gas market as well as the wholesale gas market since free competition can allow for innovative services for the consumers and prices based on the balance between supply and demand [51].

Gas pressure must be maintained between the security levels indicated in the regulatory framework of each country. If the variation between gas withdrawn from the networks and gas injection into the networks is higher than the one allowed for security reasons, an imbalance is detected and a balancing mechanism has to be deployed. This mechanism may take different forms. It may be a balancing market based on auctions or it can be solved through imbalance payment. For example, in Denmark, either the shippers or Energinet (gas network operator) must pay depending on the direction of the imbalance. The shippers may pool the imbalances under the consent of Energinet [52].

#### 4.4 Degree of similarity between the considered countries

The UK and the Netherlands are gas producers and exporters whereas other EU countries are mainly gas importers with low or no domestic production. However, the gas production in the EU was decreasing to 120 bcm in 2018 (i.e. 8% less than in 2017). UK was the main gas producer in the EU in 2018 while the Netherlands became a net gas importer [53].

In European countries that have been slower at opening the market to competition, the gas price is generally higher. Furthermore, the security of supply is lower in countries that have not opened their gas markets.

Like for electricity, changes promoted by the EC to harmonise some national rules are effective (first grid code adopted in 2013 dealing with capacity allocation mechanisms; second grid code in place since 2015 concerning the balancing rules etc.). Also, most of the studied countries use the PEGAS platform for day-head, intra-day and future products (Spain was the tenth country to join in June 2019 the PEGAS platform).

However, despite these important improvements, the European gas wholesale market 'is not yet a fully integrated single market', as suggested by the spread between the cheapest and the highest average wholesale prices over 22 European countries, which depends on the gas connection of each country, i.e. relatively low prices in the considerably integrated North-Western European countries (including Denmark and UK, then Austria and France); intermediate prices in countries with a moderated connection to the north-west zone; relatively high prices in countries with a low connection (including Italy, Sweden, and Spain) [54]. Another example is given by the specificities found in terms of the types of spot and future products traded in the different countries and of the trading times.

The EC points out the main trading barrier, the persistence of national cross border tariffs between countries inside the EU: a trader that ships through several borders must pay that accumulation of tariffs, which induces higher costs. It is also a barrier for more efficient cross-border balancing, and it makes transportation routes less efficient.

The access to storage capacities is decisive to develop a competitive market and to promote synergies between gas and electricity. However, these capacities are unequally distributed, as shown by the allocation of underground gas storage: Germany (232 TWh), France (134 TWh), Netherlands (130 TWh), and Italy (193 TWh) cumulate 58% out of the total EU underground storage capacities, namely 1182 TWh. The underground storage in the other considered countries are as follows: 92 TWh in Austria, 10 TWh in Denmark, 32 TWh in Spain, 9 TWh in the UK, and 0.1 TWh in Sweden [48].

Regarding the retail market, all seven studied countries have a liberalised market segment, where consumers can freely choose their retailers. Each retailer provides its tariff offers with different prices and conditions. Charges are usually divided into a fixed rate for network access and a variable term for the volume of supplied gas.

Regarding the balancing mechanisms, as already mentioned in Section 4.3, it may take very different forms. For instance, the balancing mechanisms may consist of the constitution of balancing groups under the responsibility of a balance responsible party as in Austria; the balance obligation of the shippers and the payment of imbalance payments such as in France and Denmark; a balancing platform operated by the market operator for the trading of stored gas and of localised products as in Italy; or the procurement of normalised short-term and balancing products by the gas system operator and call for tenders as in Spain.

#### 4.5 Resources of flexibility

In the gas system, flexibility is available due to the easy storability of natural gas. One of the most important potential flexibility resources is the line pack, which can provide the most rapidly usable gas (up to pressure limits for safety). Proportional to the gas pressure in the pipelines, the amount of line pack changes throughout the day due to the varying levels of pipeline pressure: this is an important mean of operational flexibility which already helps the gas network operators to balance gas demand and supply within a day. For instance, in Sweden, the usage of the gas pipes for short-term balancing purposes allows making up as much as 25% of consumption on a typical day in winter [55]. This also means that countries with a major length of gas transport and distribution networks such as France, Italy, and the UK can count on significant gas flexibility. In the UK, the within-day line-pack flexibility in winter between 2013 and 2018 varied between 83 GWh (min) and 690 GWh (max) [56].

To provide flexibility potential to the electricity system, conversion technologies such as gas turbines, and more recently, power-to-heat, power-to-gas, and hybrid dual-fuel heating pumps are needed.

The most common synergy between the different energy systems is presently in the direction of gas-to-power. For example, cogeneration plants can produce electricity and thermal energy in a cost effective way. However, some technologies based on hydrogen generation using electricity are now being studied. ORSTED, the biggest Danish power company seeks gas (hydrogen) production from the electricity generated in offshore wind farms, in Copenhagen, for balancing purposes [57].

Finally, coordinated scheduling of both electricity and natural gas systems can be envisaged to optimise their respective operation [58, 59]. However, it necessitates respecting numerous technical constraints from the power system (see Section 2.1) and from the gas system (line-pack management; ramp-rates to avoid sudden pressure variations in the pipelines etc.), which might reveal to be very complex.

## 5 Main characteristics of the heating system

### 5.1 Main needs, constraints, and particularities

Heat networks refer to geographically restricted networks providing energy for space heating, domestic hot water or cooling. Unlike electricity and gas, whose supply relies on a national or regional grid, DH is made of a set of non-cohesive networks, e.g. around 200 networks in Italy and Sweden, slightly <700 in France [60]. The UK differs from the other countries with a surprisingly high number of DH networks (5500) compared with the share of consumed heat they stand for (2%). This stems from the adopted definition of DH networks, such as networks that supply at least two buildings and at least one customer. If these micro-DHs are not taken into account, the number of standard DH networks is much lower and in the range of other countries (about 200 large DH networks).

In most cases, these local networks are not connected to each other except for some systems in Italy and Denmark.

In most of the case study countries (within the EU), DH seems to play a minor role in the heat supply, around 2% up to 5%. Nordic countries are exceptions. Sweden turns out to be an obvious exception as DH stands for more than 50% of the national heat supply [61]. Similarly, in Denmark, DH is the most important heating source in the residential heating sector: 64.4% of all Danish

households are connected to DH systems [62], not only for space heating but also for domestic hot water.

Heat networks are compliant with the use of several technologies of heat generation (gas-fired boilers, geothermal HPs, biomass, heat/waste recovery etc.). In most countries, fossil fuels (e.g. through large gas boilers at the district scale) still play a significant role (50–80%) in the heat generation. However, renewable and recycled energies account for an increasing share of heat generation. It should be pointed out that this share reaches more than 90% in Sweden [63] and Spain whereas these kinds of sources account only for around 12% in the UK (see Table 3).

In the considered countries, CHP plants (whether they are fossil-fuelled or RES-fired CHPs) represent a significant share (around 30% up to nearly 70% in Denmark) of heat facilities whereas the share of conventional fossil-fuelled boilers has been declining. However, as mentioned by Flex4RES [12], the present development of CHPs in the Nordic countries – and then their technological specifications – is not pushed by national energy policies to propose flexibility, but rather to increase energy efficiency and security of supply.

## 5.2 Geographical scales

Heat networks are mainly located in medium or large cities. Although the potential for recovery of heat from industrial processes exists, interconnections between industrial heat networks and DH systems are still rare. However, some synergies within local multi-firms industrial heating networks are already operated.

In the following sections, the focus is made on urban heating systems.

## 5.3 Types of markets

The markets are mainly local (decentralised). The buildings supplied by the heat networks are mainly multi-family houses or commercial buildings.

Although the role of DH is still limited in most EU countries, they are promoted by national energy policies and supported by national regulations. The latter also promotes the increase of the share of renewable and recycled energy in these networks, especially in countries where they do not play a significant role.

It seems there is no nationally regulated DH pricing. Prices seem to be set for every heat network given local conditions but they might have to be approved by the local or regional authorities. This latter can act as DH operator main stakeholder (for instance in Austria, sometimes in France, Spain, Sweden or Italy), as DH owner delegating the DH operation (for instance in France), or as a local authority delegating both the ownership and the operation of the DH. In some cases (such as the private DH networks in GB), there is neither specific price regulation nor local authority involvement. In Denmark, although heat producers are generally private in large cities (but the transmission activity is unbundled), the full consumer price of DH is regulated by the Danish Energy Regulatory Authority. In Italy, when and where the connection to a DH is mandatory, tariffs are regulated by the oversight commission. In Sweden, where private players are also present in the DH sector (beside public actors), there is no price regulation but the supervision from the National Energy Market Oversight

Body can be activated when abuse of dominant position is suspected.

In most cases, a dual tariff scheme based on fixed and variable fees is applied to DH in the analysed countries. Fixed fees are supposed to cover facilities and network investment as well as maintenance costs, whereas variable fees cover fuel purchase for heat. A mark-up is generally applied in a kind of ‘cost+’ perspective. However, in some cases, tariffs definition must consider the potential competition of alternative heat fuels such as gas and electricity in the frame of a kind of ‘netback approach’.

The price level for DH and the share of fixed and variable fees in the total price can strongly depend on the heat production technologies. For instance, in France, DH networks mainly fuelled by geothermal HPs display a much higher share of the fixed fee (64%) than the ones relying mainly on heat recovery (32%).

These observations might explain to some extent why there is no national price regulation for DH.

The case of the DH system in the Greater Copenhagen Area in Denmark is somewhat special. Unlike other DH networks in Europe, it works as a heating market. Varmelast.dk, a cooperative between DH companies, manages and operates this market [64].

## 5.4 Degree of similarity between the considered countries

Basically, the heat networks across the considered countries seem to be quite similar. In most cases, they are decentralised, non-cohesive, and not part of an integrated energy market.

Although there might be a national general regulation framework that can be applied to this sector (and generally concerning the RES share or climate change mitigation aspects), regulation and price-setting mainly rely on public–private cooperation. For instance, the local authority generally owns the DH network and may delegate its operation to a private company if there is neither a local authority-owned (partially or not) operator nor a specific private–public partnership (usually through a tendering process). Prices are set on the basis of a specific agreement between the private DH operator(s) and the local authority.

With the exception of the Danish case, competition in the heat activities is generally not developed [65]. For instance, even the third party access (TPA) to existing DH networks by heat producers is not yet in place: there are only cases of a bilateral contract between a heat generator and a heat network operator. The recent Renewable Energy Directive (art. 24) just introduces the TPA principle as a possible alternative for the member states to a national objective to increase the share of waste and RES heat (and this option contains a series of exemption cases).

## 5.5 Resources of flexibility

The heat production systems used in DH allow some opportunity for providing flexibility services.

First of all, a DH may involve several heat production sources, which can be curtailed or activated: geothermal HPs, waste recovery, heat recovery, gas boiler – including CHP. The relevant substitution of heat production sources basically helps load-shedding when it is necessary.

**Table 3** Energy mix for the heat production of heat network expressed as percentages of energy resources (based on [26])

%	AT	DK	FR	IT	SP	ES	UK
<b>Total share of RES</b>	<b>49</b>	<b>48.3</b>	<b>53</b>	<b>26</b>	<b>80</b>	<b>93</b>	<b>12</b>
waste recovery	4	11.7	25	26	2	51	1
biomass	42	33.6	21	—	71	40	10
geothermal	3	2.3	4	—	1	1	1
others	—	0.7	3	—	6	2	—
<b>Total share of fossil fuels</b>	<b>51</b>	<b>51.7</b>	<b>47</b>	<b>74</b>	<b>20</b>	<b>7</b>	<b>88</b>
gas	44	18.8	39	74	17	3	88
oil	3	0.7	1	—	3	2	—
coal	4	20.3	6	—	—	1	—
others	—	11.9	1	—	—	—	—



Moreover, systems involved in a DH are in many cases either heat-to-power (CHP) or power-to-heat technologies (HPs), which makes it easy to provide flexibility to the electricity grid (through power generation or opportune power consumption depending on the needs of the grid).

However, additional considerations must be pointed out to go beyond this theoretical potential.

It is already possible to generate electricity at a large scale with CHPs, provided that the heat demand is met (i.e. power generation is driven by heat demand). These opportunities presently seem much more limited for power-to-heat technologies such as HPs as this system service would require a large amount of HPs, which is far from being the case, due to the limited HP deployment in most European countries. However, some national regulations, such as in Denmark, try to foster the penetration of CHPs and HPs in DH networks [66].

## 6 Comparative analysis between energy sectors

The organisation of the different energy systems studied in Sections 3–5 has close similarities. For instance, the essential roles and functions of the electricity and heating sectors have been compared and hence their similarity demonstrated [67]. This can be extended to the gas sector where the technical functions ‘generate’, ‘consume’, ‘deliver’, ‘balance generation and consumption’, and ‘restore the network’ also exist. Furthermore, similar roles carrying out these functions can be found in the three sectors: producers, suppliers, consumers, storage operators, network operators etc., most of them with a balanced responsibility.

The grid management for both gas and electricity present similar stakes for interconnections, transmission, and distribution, including the unbundling rules and the third-party access to the network, in order to guarantee non-discrimination between market players, and then a fair competition, whereas for heating networks, there are mainly distribution issues, without any unbundling obligation.

The organisation of the wholesale gas markets also presents certain similarities with the electricity markets. Wholesale trading where suppliers and buyers trade directly coexists with organised markets to balance the system.

Even if both gas and electricity systems can be divided regarding their time horizon and range from long-term to short-term perspectives, the short-term and the real-time aspects are hugely more crucial for electricity.

The operation of gas and electricity systems uses day-ahead and intraday nominations before the physical delivery. In the heat sector, there are generally no organised markets as such, even though, some sorts of ‘heat market’ mechanisms can sometimes be found involving a day ahead planning and intraday adjustments between the heat producers and the operator of the mechanism: that is the case of the Greater Copenhagen Area in Denmark, mentioned above.

Finally, due to the existence of gas-fired plants, gas and electricity systems have already implemented a type of coordination in case of gas emergency, in order to limit the impact of any gas supply disruption or of a pipeline emergency on the power-generating capacity.

Despite the above-mentioned similarities, huge differences between the three energy systems exist. At first, their territorial expansion is contrasted: over the territory of the entire countries for electricity; limited to local territories for DH; intermediate development for gas depending on the country.

Secondly, the design of markets across the three sectors varies considerably.

However, within the electricity sector, we see now a growing trend to harmonise the European electricity markets since electricity systems in each state face common needs that have to be addressed. Thus, most of the day-ahead electricity markets are coupled in Europe and more recently, intraday markets have also entered a harmonisation phase [26]. This process has been extended to the balancing markets and mechanisms through pilot projects, where European TSOs are currently discussing and testing the possibility to harmonise the design of such markets.

If the process of gas market liberalisation is advancing, many hubs are not yet mature and well established. The persistent use of long-term contracts to share the gas transmission capacity limits competition even if it is expected to change in the next ten years [54]. The high share of non-European players in the gas upstream activities is another difference with the current electricity market where mostly European participants are involved.

Regarding the heat sector, heat provision is not yet in a competitive process. Speaking about ‘market’ might be also misleading since there are generally no ‘organised’ markets as such [26] even if there are some examples of day-ahead planning and intraday adjustments in the Nordic countries (Denmark). Furthermore, unlike for gas and electricity, the heat provision is usually organised as a local vertically-integrated monopoly structure, without any interconnection between DHs and without any unbundling between the roles of the heat generator, heat network operator, and heat supplier. Even the TPA to existing DH networks to promote RES and waste heat is not yet implemented, excepted when the DH network operator explicitly gives its consent [65]. Finally, there are only a few cases of regulatory incitation to develop links with the electricity markets.

## 7 Potential barriers to the development of MES flexibility provision

Potential synergies between the electricity, gas, and heat sectors arise from their commodity properties. The storability of gas and heat could level out volatile RES and prevent curtailment in times of overproduction.

MESs are per se at the core of the synergies between sectors and would play a relevant role in case of a growing complementarity of the design of energy markets. However, even regardless of technological issues, the provision of flexibility by MES might face different categories of barriers identified in several of the considered countries.

### 7.1 Various national potentials for MES flexibility

Each national energy system design results from a specific response to a particular set of conditions or constraints which affect each national electricity system in a different way. Similarly, the current development of gas and heating networks remain heterogeneous between the considered countries. On the other side, the needs for flexibility services will depend on the specificities of the electricity system in each country (its reliability, RES deployment conditions, existing generation mix etc.). Such diversity between existing market designs is not necessarily a barrier for deploying MES flexibility, but it does require MES stakeholders to develop case-by-case strategies to be able to effectively provide flexibility services. In the same way, the future role of gas in each national energy transition process could also influence the development of MES flexibility provision.

### 7.2 Current market design and regulatory barriers

This category includes potential barriers of various natures. Two examples are given here.

The design of the mechanisms and markets currently in place to procure ancillary services can be incompatible with the provision of MES flexibility, for instance

- The minimum bid size for the participation in some ancillary service mechanisms (which can go up to 50 MW for the fast reserve in GB) might be too high for MES.
- The characteristics of the product required (ramping, delivery duration etc.) might be unsuitable for MES. This is the case for example for steam turbines and combined cycle gas turbines (CCGT), which require up to several hours for cold start up [28]. They can provide flexibility within 60–120 min, which is not compatible with the requirements of balancing services. For hot start conditions, the start-up time for CCGT is about 30–45 min. CCGT can achieve a ramping rate of 6%/min, which can be insufficient for instance for FCR which needs very quick full



activation (10–180 s depending on the country). Other examples may be given by compression chillers and HPs, which also show limited ramp rates. More information can be found in [28], which details the technical suitability of different technologies involved in MES to provide services to the electricity grid.

Other examples of barriers could come from regulatory frameworks that would or not encourage electricity grid operators to use flexibility. For instance, a capital expenditure (CAPEX)-based regulation can encourage the grid operator to keep investing in the grid rather than to develop flexibility alternatives to postpone or to avoid network investments: the authors of [68, 69] point out the necessity to implement a new balance between CAPEX and operating expenses in the distribution regulation to facilitate the flexibility development.

### 7.3 Impacts of electricity network tariffs

Regulated network tariffs aim at promoting grid-oriented behaviour patterns by sending short- or long-term price signals to grid users. Their level, component structure (i.e. the relative weight of fixed, energy, and capacity terms), and time-based structure can be determinant for the provision of MES flexibility. For instance, a high electricity grid tariff, in particular with a high-energy component, could become a competitive disadvantage for power-to-heat alternatives [14].

These patterns might significantly influence the choice of technologies for heat generation for DH networks, and consequently the development of MES flexibility services.

However, the awareness of the network tariff issue is raising. For instance, in Austria, an evolution of the electricity network tariffs has been implemented in order to significantly reduce the monthly capacity cost increase caused by negative frequency regulation provided to the TSO [70].

### 7.4 Lack of coordination and highly contrasted professional culture of the relevant stakeholders

Other barriers are due to structural issues such as missing or limited coordination between electricity, gas, and heat network operators. Increasing the synergies between the three sectors should not only be considered at the market and regulatory levels but should also be investigated from a more technical perspective, for instance for network operation and sharing of technical knowledge and data. Electricity, gas, and heat network operators have rather different system cultures and processes resulting from the different time constants, granularity, inherent resilience and dynamic behaviours of the three types of networks.

At a larger scale, the traditional culture to invest, plan, maintain, operate, trade, and remunerate is rather different in the three sectors (gas, electricity, and heating/cooling). Synergies between the three sectors might then generate high learning and implementation costs in order for MES to provide their flexibility to the electricity system. However, without a sufficient mutual ‘cultural appropriation’, the risk of poor performance is serious and could create a strong lock-in effect for MES flexibility provision.

### 7.5 DH design and usual contractual heating obligations

The provision of MES flexibility to the electricity system should not interfere with DH contractual arrangements to deliver heat supply: a heat network is initially designed, sized, and operated for supplying contracted energy services (heating, cooling etc.), which will remain its primary objectives. Its ability to contribute to supply flexibility to mechanisms such as capacity requirement mechanisms, balancing or ancillary services might be challenged then limited by these contractual commitments. This point is linked to the technological ability of DH systems.

### 7.6 Risk of incompatibility between flexibility provision by MES and national policies

An example of such barriers can be provided by national policies implemented to support RES: regulation usually fosters a high

share of RES, waste or heat recovery in the DH sector in order to reach environmental objectives, and therefore do not push flexibility in itself. They might henceforth have an adverse effect on the exploitation of multi-energy-based flexibility. For instance, in France, maximising the synergy and MES flexibility provision opportunities might lower the share of RES used by a DH network under the threshold of 50%, which might exclude this DH network from several support measures (e.g. reduced value-added tax) and harm its economic profitability and stability. In Nordic countries, tax exemptions for biomass could make the DH prefer to substitute biomass heat-only boilers for gas-fired CHP, namely a substitution to reach an environmental objective but which reduces the MES potential for flexibility [13].

### 7.7 Flexibility service costs and cost competitiveness

As a consequence of the above-mentioned elements, the remuneration of MES flexibility potentially available through the energy, ancillary, and capacity markets shall be sufficient to recover the additional costs experienced by the MES to provide the associated services. This means not only recover the operating costs but also the possible ‘implementation’ costs (e.g. installation of dedicated monitoring, control, and information and communication technology equipment and/or mandatory measuring devices in the DH system) and the cost needed to develop and ensure a sufficient level of coordination between the three energy sectors.

More generally, the economic opportunity for an MES to supply flexibility would be also challenged by

- The energy prices, which constitute a crucial parameter. For instance, the development of power-to-heat options could be affected by high prices of electricity when on the contrary, CHP would be penalised by low prices.
- The relative weight of the MES fixed costs: the MES with fixed costs relatively high compared to variable ones could consider the gain opportunity in trading off between alternative energy sources for heat generation. In fact, operating and maintenance costs vary widely depending on the type of heating networks. This repartition of variable and fixed costs is specific to each MES: it could significantly influence the interest of each MES to provide flexibility or not (e.g. to generate or to buy electricity to run its HPs).
- Finally, the relative cost competitiveness of MES compared to other flexibility resources such as storage and demand response.

## 8 Conclusion

Provision of flexibility services through increased synergies between different energy carriers, such as electricity, gas, and heat, appear as one possible mean to answer the growing flexibility need of the current and future power systems.

The comparative analysis carried out between the three energy sectors shows that electricity and gas sectors present global similarities notably in terms of markets, industrial organisation, competition, and interconnection between local, regional, and supra-national networks. On the contrary, the DH activities present radically different organisation and modes of investment, operation, and trade. If we exclude the Danish case of the first experiment of the heat market, a DH system generally remains local and disconnected from other DHs. Most DH players remain vertically-integrated and not faced with competitive challenges. This situation creates a significant difference between DH activities and electricity and gas ones: the necessity to coordinate the three sectors could become a crucial issue for the provision of MES flexibility.

Beside the differences between the energy system fundamentals, the analysis also highlights the persistent diversity of national mechanisms in place, and particularly of regulatory schemes. This diversity appears as a real challenge for the provision of MES flexibility, even if processes to harmonise some key issues are on-going, particularly in the electricity sector. This issue could require MES stakeholders to develop case-by-case

strategies and approaches to addressing the different markets in different countries.

Then, the proper remuneration of the MES flexibility, the cost of service provision experienced by MES and hence the cost competitiveness of MES flexibility compared to other flexibility resources are crucial questions to be investigated.

Finally, besides the regulatory framework and the market design aspects, there are other challenges that need to be taken into account. Technology capabilities and constraints were not considered in the present paper but are key parameters for the feasibility of MES flexibility provision. They are the subject of other studies carried out in the MAGNITUDE project and will be assessed on the seven real-life case studies in Austria, Denmark, France, GB, Italy, Spain, and Sweden. These case studies represent four main categories of MES and/or combinations of such MES, namely: large industries, large commercial and/or public sites, DH/cooling systems, and small individual units. They will allow covering different sector-coupling technologies, stakeholders, business models, and regulatory frameworks.

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