D7.4

MAGNITUDE Policy Recommendations

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D7.4 – Policy Recommendations

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Lead Beneficiary: **EHP (Euroheat & Power):** Jack Corscadden, Alessandro Provaggi

Contributing beneficiaries: **EIFER (Europaisches Institut für Energieforschung EDF-KIT EWIV):** Stephan Seidelt

VITO (Vlaamse Instelling voor Technologisch Onderzoek N.V.): Kris Kessels, Ana Virag

Ricerca sul Sistema Energetico (RSE S.p.A.): Edoardo Corsetti

EDF (Electricité de France): Regine Belhomme

cyberGRID GmbH & Co KG: Christoph Gutschi

Danmarks Tekniske Universitet (DTU): Sergey Klyapovskiy

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Executive Summary

This deliverable builds on the Lessons Learnt document (Deliverable D7.3) and other deliverables of the MAGNITUDE project, analysing the project results and translating them into tangible recommendations for EU-level, based on a holistic approach, thereby enabling wider renewable energy integration thanks to new services from cross energy carrier systems. The deliverable aims to ensure the uptake of the MAGNITUDE results at policy level and provides a meaningful contribution to the ongoing energy policy discussion, both at European and member state level. The document is based on Deliverables D1.4, D2.1, and D6.2 in conjunction with project Work Packages WP1, WP3, WP4 and WP5, gathering information and analysing the overall relation among them, and contextualising the results on the national specificities.

Section 2 outlines the capacity of Multi-Energy Systems (MES) to provide flexibility to the electricity system. The most relevant services deliver reserves for frequency control and balancing; congestion management; short-term and long-term energy trades; and system adequacy. Certain actions can be taken to enhance flexibility provision such as the implementation of storage. The provision of flexibility services is a novelty for most MES and rebound effects on individual systems must be managed. A multi-disciplinary, cross-sectorial approach is needed to maximise flexibility provision by MES across Europe. An overview of the replication of MAGNITUDE case studies, including detailed information about the replication potential in specific European countries is also discussed.

Section 3 describes the aggregation of MES. Aggregation increases the ability of MES to participate in energy markets/trade flexibility services, by allowing decentralised installations, not reaching the size thresholds required for accessing the different markets, to participate. The majority of project findings are market specific. The current very diverse structure with lack in harmonization of flexibility markets in the European internal electricity market is a barrier to the scaling/replicability of algorithms and business models. Aggregation is not fully allowed in some countries and there are restrictions on certain technologies. Regulatory changes are required to allow MES to participate to all energy market mechanisms. Data availability is a key factor determining the participation of MES in the markets and so the roll out of smart meters is also important.

The section on market and regulatory perspectives (Section 4), describes the differences and similarities between the electricity, gas and heating and cooling sectors including the stakeholders, roles, and structure within each sector. New frameworks and channels are needed to improve collaboration and transparency between different actors. Innovative business models are also needed to promote and enable integration of different energy sectors. While aggregation can side-step many of the barriers limiting market participation, there is a need for the harmonisation of European electricity markets. Innovative market designs have been proposed to increase the synergies between the day-ahead energy markets in the electricity, gas and heat sectors. The developed framework can be used either as a benchmark for a perfect integration of Day-Ahead (DA) multi-carrier energy markets or to assess the value of introducing a new technology (including conversion or storage technologies) in the existing DA markets. Regulatory sandboxes should be encouraged to implement and test the new multi-carrier market concepts, improved flexibility procurement mechanisms and market-based energy sector integration in real-life.

As mentioned in the EU Strategy for Energy System Integration (European Commission, 2020b), the European "*energy system is still built on several parallel, vertical energy value chains, which rigidly link specific energy resources with specific end-use sectors*. This siloed system of separate markets and independently planned and managed networks cannot possibly contribute to deliver a climate neutral European Union by 2050. Multi-energy systems offer a technically efficient and economically viable solution that can provide a source of flexibility to the electricity system, and balance to the future integrated and highly optimized energy system.

Table of content

Table of figures

Table of tables

List of Acronyms

Abbreviation / Acronym	Description
aFRR	automatic Frequency Restoration Reserve
BRP	Balance Responsible Party
CCGT	Combined-Cycle Gas Turbine
CHP	Combined Heat and Power
CRM	Capacity Requirement Mechanism
DA	Day Ahead
DC	District Cooling
DER	Distributed Energy Resources
DH	District Heating
DHC	District Heating and Cooling
DSF	Demand Side Flexibility
DSM	Demand Side Management
DSR	Demand Side Response
EU	European Union
FAT	Full Activation Time
FCR	Frequency Containment Reserve
GHG	Greenhouse gas
H2P	Heat to Power
ICT	Information and Communications Technologies
ID	Intra-Day
MES	Multi-Energy System(s)
mFRR	manual Frequency Restoration Reserve
P2H	Power to Heat

PV	Photo-voltaic
R&D	Research and Development
RES	Renewable Energy Source(s)
RR	Replacement Reserve
TSO	Transmission System Operator
vRES	variable Renewable Energy Sources
WWTP	Wastewater Treatment Plants
TYNDP	Ten Year Network Development Plan

1 Introduction

There is a clear need to decarbonize the European energy system. To deliver the goals of the EU Green Deal, achieve climate neutrality by 2050 and deliver a prosperous and resilient Europe in the aftermath of the COVID-19 pandemic, this decarbonisation must extend to all sectors of the economy and be carried out in an efficient and cost-effective manner. A sustainable, future-proof energy system is one that is highly integrated, renewables-based and involves the transparent participation of a wide variety of decentralised actors.

The decarbonisation of the electricity sector is progressing rapidly, with significant deployment of renewable energy sources across Europe, particularly intermittent sources such as wind and solar. In terms of newly installed capacity, solar PV is now one of the cheapest form of electricity generation (IEA, October 2020). However, progress has been slower in other sectors, and fossil fuels dominate energy use in transport, industry, buildings, and agriculture. To deliver the goals of the energy transition, different aspects of the energy system need to be integrated and the resulting synergies exploited.

An optimized and integrated energy system offers new routes for the deployment of renewable energy resources and reduces primary energy demand, thus increasing the resilience of the overall system. The enhanced integration of different energy networks brings increased circularity to the energy system, through cogeneration, power-to-x technologies, renewable gases, and the recovery of waste heat. Electrification of other end-uses, from electric vehicles in the transport sector to supplying heat using electric boilers and heat pumps, is expected to make a significant contribution to decarbonising hard-to-abate sectors that have seen little progress to date.

The development of renewable energy sources (RES) and electrification of end-uses will place increased pressure on existing electricity infrastructure; and grids in many countries will need to be upgraded and expanded. Many studies show that there is a growing need for more flexibility to ensure the efficient and reliable operation of the electricity system. Enhanced synergies between different energy carriers appear now as one of the possible means to provide this flexibility.

In this context, the MAGNITUDE project developed business and market mechanisms, as well as supporting coordination tools to provide flexibility to the European electricity system, by enhancing the synergies between electricity, heating/cooling and gas systems.

MAGNITUDE addressed the challenge to bring under a common framework, technical solutions, market design and business models, to provide flexibility services to the electric grid from multi-energy systems. This framework supports the cost-effective integration of variable RES and the decarbonisation of the energy system, while increasing security of supply.

This document aims to ensure that the project results provide a meaningful contribution to the ongoing policy discussion in the overall energy field and provides recommendations to policymakers on how to promote and maximise the benefits of flexibility provision by Multi-Energy Systems (MES).

The provision of flexibility services was assessed using the following real-life case studies:

- District Heating and Cooling networks: high-temperature networks in Västerås, Sweden (Mälarenergi) and Milano, Italy (ACS), ultra-low temperature network in Copenhagen, Denmark (HOFOR), and combined cooling and low-temperature heating network in Paris-Saclay, France.
- Paper mills, on the basis of a pulp and paper mill in Austria.

- Waste-Water Treatment Plants (WWTPs), relying on a WWTP in Murcia, Spain (EMUASA).
- Gas-fired plants, as available in Neath Port Talbot, Wales (NPT).

2 Provision of flexibility by multi-energy systems

2.1 Capacity to provide flexibility

Sector coupling technologies provide flexibility services to the electricity system either by increasing or decreasing their production of electricity, by converting electricity into other energy carriers (heat, cooling, gas) or inversely by consuming energy from other carriers (gas) to reduce their electricity consumption, or by reducing, increasing or shifting the electricity demand to a time that is beneficial to the electricity system. The most relevant services deliver reserves for frequency control and balancing, network congestion management, short-term and long-term energy trades, and system adequacy.

The ability of MES to provide flexibility is determined mainly by the following parameters:

- Ramp-rate: how quickly an output can change.
- Start-up time: time to reach full plant load, impacted by whether the plant is starting from a cold or warm state.
- Power range: MES alone may not meet certain thresholds, aggregation of smaller units can deliver higher capacities.
- Capacity to balance the rebound effects on the energy carriers impacted from electrical flexibility provision.

The existing technologies that provide flexibility can be divided into 5 categories: Power to Heat (P2H), Heat to Power (H2P), energy storage, energy networks and heat-to-gas.

Flexibility is provided via 3 main levels:

- fuel shift: for instance, depending on the MES, upward flexibility can be provided by reducing electricity consumption and increasing gas consumption, while producing the same amount of heat to the heat consumers.
- demand response, for instance through the shifting of the electricity consumption, which in turn may result from heat peak shaving on the district heating network.
- storage capability, for instance, using the capability of thermal storage to decouple the production and consumption processes of an industrial site.

MES consider the four energy sectors (electricity, gas, heating, and cooling) and provide flexibility through the control of their technological components and the optimisation of their operation. The characteristics of similar MES impact directly the flexibility pool that can be activated. The way MES are designed influences the flexibility provision potential now and in the coming years. The MES considered procure or provide heat, cooling and/or gas and provide services to the electricity system.

There are two types of MES, consumers and producers. Consumer MES, e.g. HOFOR, provide upward flexibility by reducing their electricity consumption and downward flexibility by increasing their consumption. For producer MES, e.g. Mälarenergi, upward flexibility is provided by increasing electricity production, while downward flexibility is provided by decreasing production. MAGNITUDE results show that the provision of flexibility generally increases the MES energy consumption and operational costs. But introducing storage technologies may limit or even avoid this increase, depending on the case. The provision of flexibility has little impact on the overall energy efficiency of the MES, since they would only propose these services if their demand can be satisfied either through storage technologies or by shifting their energy use between different systems during a limited number of operating hours (e.g. shifting between a heat pump and a gas boiler).

Certain actions can be taken to enhance flexibility provision by MES. For thermal plants, a number of measures can be implemented to increase flexibility provision, such as switching from solid to gaseous fuels for thermal power generation, or increased integration of heat storage, both at large and small scales, is needed in district heating networks or industrial processes to increase flexibility provision. Policy support, including financial incentives, is needed to support and accelerate the roll out of thermal storage. High temperature storage technologies are still at Research and Development (R&D) stage and further development of heat storage at temperature levels above 300°C would also increase the capacity. This technology is key for enabling huge flexibility potential in industries.

As already mentioned, energy storage technologies decouple production from consumption, increasing the level of flexibility within the system. Each MES deploys different technologies as well as different strategies to manage and coordinate their operation. The integration of these technologies within the overall energy system and their interaction with other sectors can be improved by better control strategies and the deployment of appropriate Information and Communications Technologies (ICT).

The synergies between the electricity and heating and cooling sectors represent a significant untapped potential for the provision of flexibility. Further R&D is required to effectively integrate high temperature, large-scale and low-cost heat pumps. Large scale heat pumps connected to District Heating and Cooling (DHC) networks might offer a more efficient method of heat supply, compared to small-scale individual heat pumps. This represents a top priority for the DHC sector and should be a focus of both R&D and policy support in the near future. Electric boilers powered by renewable electricity and CHP units should also be expanded.

The simulated MES show a high ability to provide flexibility at a moderate cost. However, the energy, environmental and economic efficiency of the provision of flexibility services differ depending on the type of systems considered. Only a small portion of the available flexibility could be activated by the MES in the simulations, due either to low market liquidity, low market prices, technical or regulatory limitations. All case studies could provide flexibility at competitive costs during some hours of the year. In general, the revenues from flexibility provision turned out to be lower than expected, which promotes the conclusion that day-ahead optimization of the core operation is more relevant to MES under the current market rules, than flexibility provision. Payments for reservation of capacities for ancillary services (e.g. frequency reserve services) can improve the amount and predictability of revenues for the MES. The low revenues are also caused by a low probability of activation by the transmission system operators, which also means that the MES operation would not experience continuous disturbance from flexibility provision.

The provision of flexibility by the case studies generally had a marginal impact on the overall energy and environmental efficiency of the MES, especially when compared to the introduction of improvement strategies (e.g. thermal storage) or the change in the scheduling of some energy devices to provide ancillary services (as seen for the ACS case study). In general, in the considered case studies with CHP plants, activating positive (upward) flexibility will lead to increased energy consumptions (mainly natural gas), energy expenses and greenhouse gas emissions while the opposite trend is observed for negative (downward) flexibility provision. MES offer a reliable, decentralised source of flexibility. A deeper analysis of their potential to provide widespread flexibility, and the system barriers to doing so, is needed. Legislative changes are required to enable their participation to all energy and ancillary service market mechanisms and maximise the amount of flexibility provided. From the MES perspective, participation to multiple markets can offer significant economic benefits.

2.2 Flexibility optimization

MES behaviour can be optimised towards the identified electricity market services (outlined in Table 1). This optimisation enables the evaluation of the benefits, arising to the MES-operator and possibly to the (national/regional) electricity system operator, by the quantification of the amount of flexibility really made available and the remuneration/cost-reduction. Algorithms and models enable the simulation and assessment of each MES in base-case configuration and under new technological combinations, with regards to the provision of market services as identified in Table 1, and with boundary conditions and scenarios. The simulations and assessments allow the evaluation of key performance indicators. This enables to identify and maximize flexibility, which allows to manage multiple market services at the same time.

Table 1: Selected electricity system needs and services (Cauret, et al., 2019)

Needs	Services
Balancing and frequency control	Provision of reserves for Transmission System Operators (TSOs) • Frequency Containment Reserve (FCR) • automatic Frequency Restoration Reserve(aFRR) • manual Frequency Restoration Reserve (mFRR) and Replacement Reserve (RR) + dedicated additional balancing mechanisms which may exist in certain countries
Congestion management	Re-dispatching mechanisms or active power control at both transmission and distribution levels
Energy trades - Reducing price risks & optimizing energy portfolios	Energy procurement mechanisms and markets: • Day ahead energy trades/market • Intraday energy trades/market
System adequacy	Capacity requirement mechanisms: • Capacity markets (together with other revenue streams) • Strategic reserves (without other revenue stream)

In certain cases, all the market services foreseen for the case studies are traded at the same time. This allows to better exploit arbitrage among the different markets and products. Services are provided by the flexibility accounted from multiple devices, taken in isolation or in a technological pool. The flexibility computed satisfies the device and market product requirements, and represents the maximum amount possibly provided by the devices for the specific market product. For others, the relevance of the results lies in the characteristics of the MES. For instance, in HOFOR, services potential remains fairly constant across different seasons while for Mälarenergi and ACS, flexibility services potential exhibits a highly seasonal nature. The MES participation in markets of energy and services, generally requires the support of an aggregation platform, and the electrical system actually benefits from the flexibility provided by the studied MES.

For most MES, the provision of one or more flexibility services is a novelty. Rebound effects on heating, cooling, gas and also electricity systems arise from the introduction of improved configuration at the technological or management level, and of electricity market participation. These effects must be optimally managed to ensure that the system continues to deliver its primary function, e.g. heat supply. The amount of available flexibility actually transformed into market services could be greatly increased by a suitable regulatory framework. For instance, some requirements on flexibility imposed by specific market products, like symmetry or duration, deeply impact the MES flexibility finally proposed as market service, even if they can be overcome allowing more than one service at time. For instance, in the case of a product which requires a symmetric electricity provision in import and export, it can be equivalently covered by two products: one devoted to cover the importing mode and the other the exporting one. Something similar can be foreseen for products, which require a duration in time: it could be possible to require as many instantaneous products as needed to cover the duration interval required by the single product. The issues discussed above could also be solved when the MES participates to markets through an aggregation layer. This increases the ability of a MES operator to provide its flexibility when facing the regulatory framework. When smaller systems are aggregated, the individual bids could be subject to less restrictive constraints than the aggregated ones. However, even if this appears as an opportunity for the MES, this leads at the same time to an extra cost (aggregator remuneration) for those MES which could directly access service markets.

The economics associated to market services are another critical aspect to encourage or constraint the provision of MES-flexibility. In the daily operation of MES, the participation to market services represent an extra opportunity, besides the main aim to supply the demand. In many regulatory/market frameworks, the economics related to market service remuneration/payments (depending on the importing or exporting mode of the service) were initially set for bulk power plants mainly devoted to electricity production. Especially for importing mode market services, the cost components that must be paid reduce (in some cases for a relevant extent) the opportunity for the MES to exploit its electricity importing ability. In detail, the cost components set for importing services include not only the price for the electricity carrier, but also tariffs for transmission, distribution and dispatching of electricity, contribution to incentives to promote country-specific investments, and taxes. The provision of importing-mode services in some countries appears merely as electricity consumption and not as the provision of a service that system operators are increasingly in need. A revision of the current assumptions about importing service economics closer to MES needs would bring benefits to the overall system.

2.3 Replication of MAGNITUDE studied MES

A multi-disciplinary, cross-sectorial approach is needed to maximise flexibility provision by MES across Europe. This section will provide an overview of the replication of the MAGNITUDE case studies, including detailed information about the replication potential in specific European countries.

2.3.1 Replicability of the investigated case studies

Replicability refers to the transferability of the project’s business use cases to other countries and contexts. The business use cases relate to specific case studies, i.e. a MES operating in a determined technological, institutional, contractual, regulatory, and social framework (Belhomme, Raux-Defossez, Motte-Cortés, & Kessels, 2020). This replicability is impacted by many different factors, the main ones summarised in the table below (Pini, Seidelt, & Witkowski, 2020).

Table 2: Factors impacting on replicability

Factor	Impact on replicability
Technologies and Multi-Energy Systems	The characteristics of similar MES impact directly the flexibility pool that can be activated. The way MES are designed influences the flexibility provision potential now and in the coming years (according to the expected lifetime of these plants).
Market: energy prices	The relationships between electricity, heat and gas prices determine which technologies (energy conversion processes) will be preferred for a certain application. The share of taxes and other costs directly impacts the benefits which could derive from flexibility provision. The smart-meters roll-out is directly related to the possibility for decentralised MES to exchange real-time data, which is a prerequisite for most of the studied flexibility services.
Market: flexibility services	Differences in Full Activation Time (FAT), product deployment duration, minimum offer size, market product’s shape, markets access and transparency characteristics determine whether the MES is able to participate to the service and under what conditions.
Market level: aggregation	Due to the current characteristics of electricity markets, some MES can trade the flexibility they can offer only if aggregated.

The flexibility that MES can offer through fuel shift, storage and demand response can be valorised and traded through different electricity markets and services. Depending on conditions imposed by the markets and on the characteristics of the MES itself, the MES can offer flexibility to the different markets either directly or through an aggregator. The following indicators have been identified as conditions favouring the provision by MES of the flexibility services identified in the project.

- **Possibility for Demand-Side Response (DSR), aggregated generation and loads to participate**: Some devices and MES cannot directly offer their flexibility in the energy markets or through ancillary services, because of a lack of unitary installed capacity, or too complex bidding procedures to be handled by a single installation, whose current main purpose is not power sale. The possibility for aggregated devices to participate is therefore particularly relevant for decentralised loads and producers, such as P2H units, cogeneration units and storage devices located in district heating and cooling networks, waste-water treatment plants and paper mills.
- **Frequent short-term auctions and tender processes for products and short product durations** are supportive for MES since loads (especially heating and cooling demand) and renewable electricity

production (from wind and photovoltaic installations) can be more easily forecast on short notice. Additionally, fuel shift can be more easily handled, without consequences on end-users' comfort or processes' performances, for a short time. It is then particularly important to have frequent auctions (or continuous trading in the intraday market) and shorter granularity of tendered products.

- **Technology neutrality:** All technologies should have the possibility to participate, after having passed the pre-qualification process.
- **Absence of price limits** (price caps and floors or bidding restrictions), is needed in order to have prices reflecting as much as possible the created value. In the recently closed consultation on the Italian market reform plan (DG Energy, 2020), the European Commission states that formation of negative clearing prices (in the ID and DA markets) could have positive effects in terms of better signals for the flexibility of the electricity system and the absence of price caps is fundamental to allow the market to provide price signals necessary for generation investments. On the other hand, it should be noted that the absence of price floors affects the volatility of prices and then increases the market risks for investors. In terms of technologies, the absence of price floors may be particularly interesting for inertial installations, so that they can sell energy, even at low – or negative – price in hours of very low demand, in order to keep the production running and be ready for following hours of high demand.
- **Existence of a capacity requirement mechanism (CRM) open to MES:** (Delta-EE, 2018), to direct and encourage investments in different kinds of assets. Capacity markets can also be important as alternative remuneration system for assets not activated in other products. Procurement of balancing products through **open tender processes** and not through opaque bilateral agreements or mandatory provision (SmartEn, Delta-EE, 2019) is important for transparency; clear rules favour the entrance in the market of new and smaller participants.

The above conditions favour flexibility provision by MES. The replicability of this provision is determined by a suite of other factors dependent on the national context and structure of energy markets. The lack of data on a national level is a significant barrier to MES replicability and represents an important bottleneck for the integration of different energy sectors (Zhou, et al., 2019). There is currently a lack of relevant and comparable data for all types of MES, in almost all European countries. The availability of data is also a key factor determining the participation of MES in the markets: the better (high granularity, pertinent measures) the systems are monitored, the more data are available. Data availability enables the development of transparent and baselined procedures for market access, to increase trust of potential new participants and to develop baselined products, to increase replicability of successful solutions across Europe. Data availability is also a pre-requisite for the deployment of aggregators, which are required for the participation of MES in flexibility markets (Anisie & Boshell, 2019), since they are the foundation for the development of advanced forecasting tools to predict generation from RES and loads. The roll-out of second-generation smart meters, broadband communication infrastructure and network remote control and digitalisation is essential to overcome this barrier.

Within the national context, there are numerous factors that can potentially promote MES replicability. The share of taxes and other costs directly impacts the benefits which could derive from flexibility provision. A low share of taxes, network costs and other non-energy related costs within energy bills, favours replicability and allows for the alteration of consumer behaviour via price signals. Smart-meters roll-out is directly related to the possibility for decentralised MES to exchange real-time data, which is a prerequisite for most of the studied flexibility services. The relationships between electricity, heat and gas prices determine which technologies (energy conversion processes) will be preferred for a certain application. The majority of the considered MES generate or supply heat, through gas, heat pumps or district heating networks. The price ratio between different energy carriers will thus favour certain technologies in any given market. Large shares of variable renewable electricity within the energy system favours replicability, as this electricity can be stored and shifted towards times of high demand. Similarly, a large number of low-temperature DHC networks can deliver system wide benefits in terms of flexibility services, as well as the integration of renewable electricity. These networks should be enlarged and expanded.

2.3.2 Replicability of MAGNITUDE studied MES across Europe

2.3.2.1 Energy Prices

As mentioned above, the relationships between electricity, heat and gas prices determine which technologies will be preferred for a certain application. Thus, the profitability of different energy conversion processes is determined by the price ratio between different energy vectors and the share of taxes and other costs directly impacts the benefits which could derive from flexibility provision. The electricity, gas and heat prices as well as their structures differ largely between the case study countries; so, for each country the replicability possibilities for the use cases are also not uniform. Electricity and gas prices are well documented by Eurostat and at national level. Whereas data on district heating prices is less extensive and detailed, due to the local nature of heat and the different degrees of market share.

For MES that involve flexible power generation like biomass/gas CHP or gas CCGT, a low-price ratio of gas-to-electricity is favourable to their development. Similarly, to realise the flexibility potential of gas cogeneration units, a low gas-to-heat price ratio is favourable. Cheap gas/biomass can be converted into more expensive electricity, increasing the profitability of the system. Low ratios result from low gas prices (e.g. missing CO2 emission fees, lower taxation) or high electricity prices (e.g. through high taxes, or grid fees). Figure 1 shows the ratios found in different European countries. In countries where gas is used to meet a large share of heating and electricity demand, the ratio is extremely low (Belgium, Germany, Italy, UK). The replication potential for these types of MES is high in these countries, as the conversion ratio makes CHPs more profitable.

Where flexibility is provided via heat pumps, a high price ratio of heat-to-electricity favours replication. The comparatively lower electricity price is favourable to the deployment of power-to-heat technologies. As shown in Figure 2, the potential for replication is highest in Denmark, France, and Sweden. In order to increase the heat-to-electricity ratio, the price of CO^2 must increase, e.g. by taxes. At present, heat is extremely cheap in many European countries. This distorts the economic value of stored heat with the system. By implementing flexible heat prices, stored heat can be given an appropriate value, while delivering huge benefits in terms of flexibility.

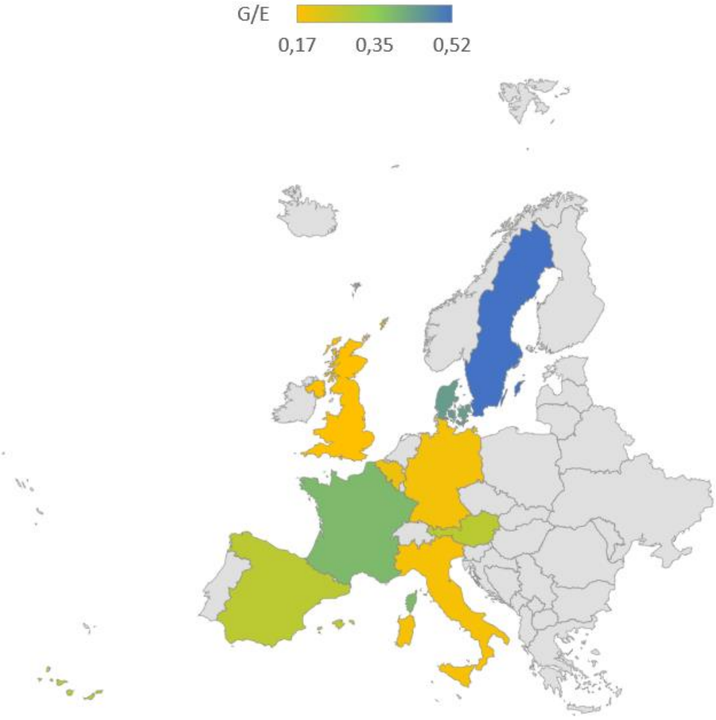

Figure 1: Gas/Electricity price ratio for non-households; own calculations

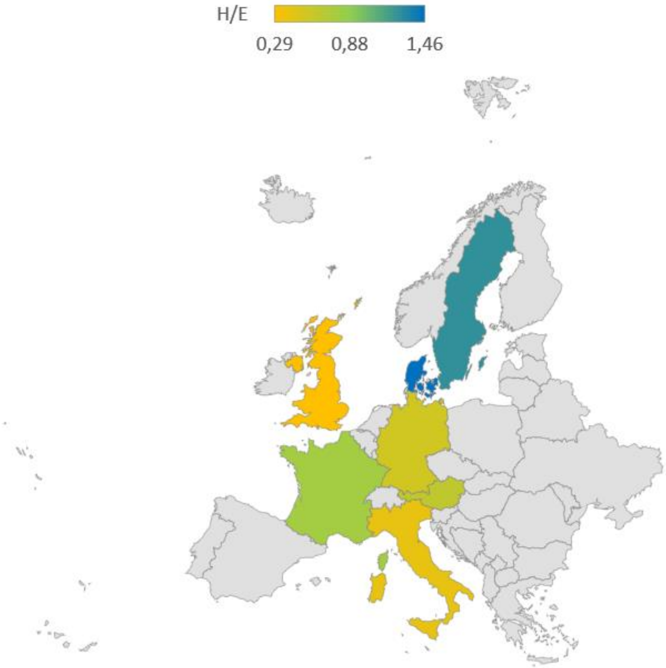

Figure 2: Heat/Electricity price ratio for non-households

The energy-related part of the electricity bill is an important leverage to modify consumption pattern, accompanied by tariffs to support change of consumer behaviour. However, more supportive dynamic tariff structures are still under development in many European countries (SmartEn, 2019). In countries where the energy component makes up a large proportion of the bill (Italy and UK), there is significant potential to influence consumption behaviour using price signals. High taxes on energy reduces the ability to maneuver, as seen in Denmark, where despite a high penetration of smart meters, the blunting effect caused by high electricity taxes makes conditions less favourable. There is a strong case for the restructuring of electricity bills in European countries. The energy-related share of the bills could be significantly increased by lowering taxes, grid fees and other non-energy related aspects. This would provide the necessary leverage and flexibility to proactively modify how consumers consume energy and deliver system-wide benefits.

2.3.2.2 DHC networks

DHC networks are inherently local, diverse systems adapted to their surrounding environment. Replicability of such systems depends on multiple criteria, depending on the configuration of the considered MES. Two of the project case studies included CHPs and two were related to low-temperature district heating with decentralised heat pumps.

Where DH is fuelled by CHP, the more electricity produced, the higher the total replicability potential. Additionally, high fuel prices (gas, biomass) together with low electricity prices are challenging for CHP profitability (high costs vs. low revenues). As shown in Figure 3, Germany has the best replicability potential, due to its high share of CHP production in the DH sector. Austria, Denmark, and Italy follow, favoured by the low gas-to-electricity price ratio. France and Spain have lower potential. Despite large amounts of CHP production, low electricity prices combined with high fossil fuel prices are a hinderance. For Belgium and UK, lack of data availability prevents an evaluation.

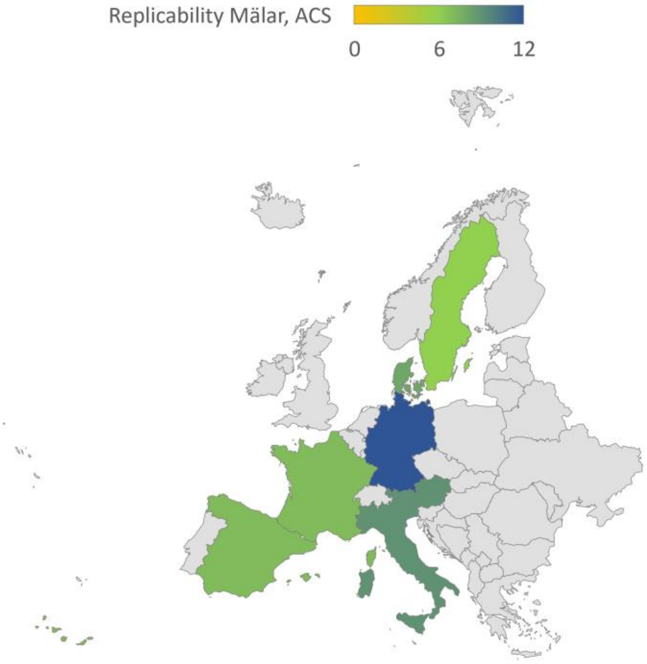

Figure 3: Replicability potential of Mälarenergi and ACS case studies (based on the overall electricity production from CHP plants connected to district heating networks and the gas-electricity price ratio)

Due to lack of data, a qualitative approach was adopted for evaluating the replication potential of low-temperature DHC networks. The indicators used, that correspond to a large replicability potential, include renewable share, rate of increase in recent years, heat-to-electricity price ratio and the degree of modernisation (generation). As outlined in Figure 4, Sweden boasts the largest replicability potential due to its low-temperature networks and high shares of renewables. Next are France and Italy (recent growth of DH), followed by Denmark (favourable heat-to-electricity price ratio). Germany, Austria, and Spain are less promising, due to their low share of solar, geothermal and heat pump generation for DH networks and higher shares of thermal generation from fossils or biomass. Both aspects hinder the transformation towards 4th generation DH. Furthermore, the heat-to-electricity price ratio is disadvantageous for P2H technologies.

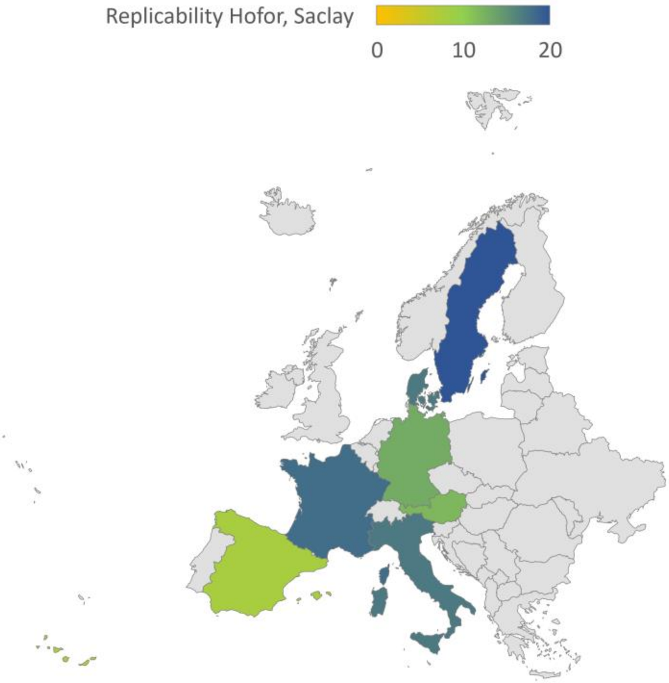

Figure 4: Replicability potential of 4th generation networks (HOFOR and Paris-Saclay case studies), with distributed units (based on qualitative indicators: current average generation, rate of DH increase in recent years, heat-electricity price ratio and renewable share in DH)

2.3.2.3 Paper Mills

The MAGNITUDE countries account for 75% of the European pulp & paper mills, with a total number of 644 mills. Most of them are located in Germany and Italy, followed by Sweden, France, and Spain. However, in terms of energy consumption within the sector, Sweden and Germany have the highest demand, despite the very different structures of their industry sectors.

Replicability potential is directly related to the self-production capacity of paper mills. No data exists on installed capacities in pulp and paper mills. Therefore, the total electricity demand of the sector in each country is calculated based on production amounts and specific electricity demands. The flexibility potential of the paper and pulp industry was also calculated.

Within the sector, integrated paper mills are less flexible, but contain surplus of energy. Heat storage is required for flexibility provision as the production of electricity and heat is coupled. Power-based applications (e.g. chippers in chemical pulp production, grinders, and refiners in mechanical pulp production, pulpers and refiners in recycled fibre preparation) are suitable for Demand Side Management (DSM). These units require high electrical power and controllability, and downstream storages enable the storage of the intermediate products (e.g. wood chips, mechanical pulp, etc.). Increased incentives are needed for DSM of pre- and post-processing units. As shown in Figure 5, the biggest potential by far is in Sweden. If Swedish pulp mills enable their full potential for DSM from load shifting, the flexibility potential is doubled compared to just a more flexible CHP operation. For other countries, this potential is lower (33-80%) compared to the flexibility from self-produced electricity. To promote paper mill flexibility in the future, investment security must be provided due to the economic competitiveness of the global paper and pulp market.

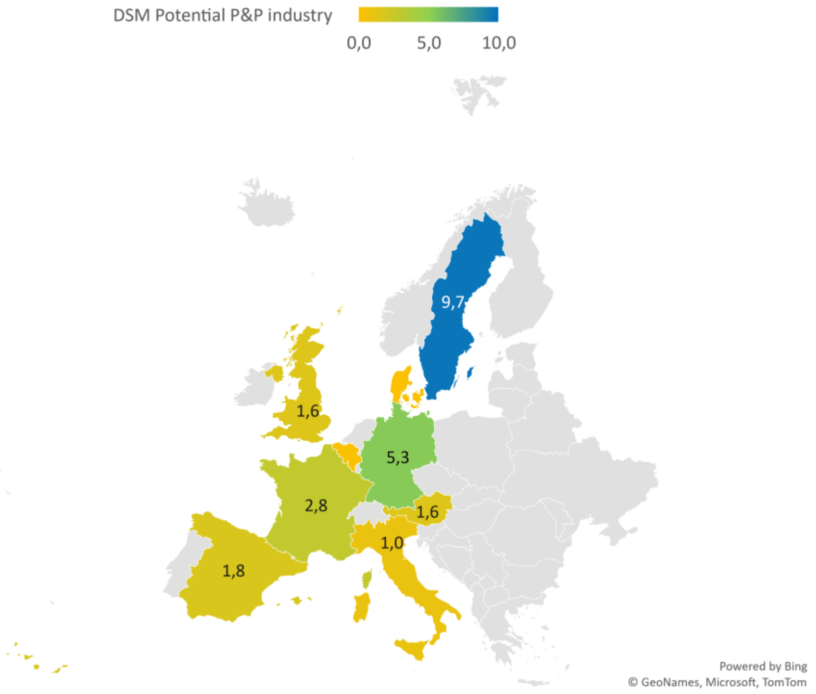

Figure 5: Technical DSM potential for paper and pulp industry in MAGNITUDE countries [in GWh]

2.3.2.4 Wastewater Treatment Plants (WWTP)

The countries considered have approximately 20126 WWTPs, 17919 of which have a treatment capacity lower than 50k Population Equivalent (PE). EMUASA case study has a design capacity of 833000 PE and an entering load of 458561 PE, and can be compared with 144 urban wastewater treatment plants and 4583 locations to produce biogas. However, not all plants with a flexibility provision potential produce biogas and some of them may upgrade biogas into biomethane instead. Countries such as Spain, Italy and Germany have the biggest potential to provide flexibility to the electricity market. Italy has the highest number of WWTPs, but many of them are small plants with a capacity below 2 kPE. In Sweden and Denmark, big plants produce biomethane, so there are no similar plants to the MAGNITUDE case study.

2.3.2.5 Gas-fired Plants

Gas-fired units plants play a different role across the analysed countries and have various shares in the overall electricity production. Natural gas is the largest contributor to energy production in Italy, UK, and Belgium. Average capacity factors show that gas plants are well exploited in almost all countries besides Austria, Spain, and Sweden.

Figure 6 shows on the left the total installed electric capacity (IEC) of the selected units and on the right their temporarily installed capacity utilisation (TICU), which corresponds to the average capacity factor in the country. When considering the installed capacities, the most favourable countries are Italy, the UK and Spain. However, from the perspective of the capacity available for activation changes when studying load factors, the highest replicability is to be found in the United Kingdom and Italy, followed by Spain and Germany.

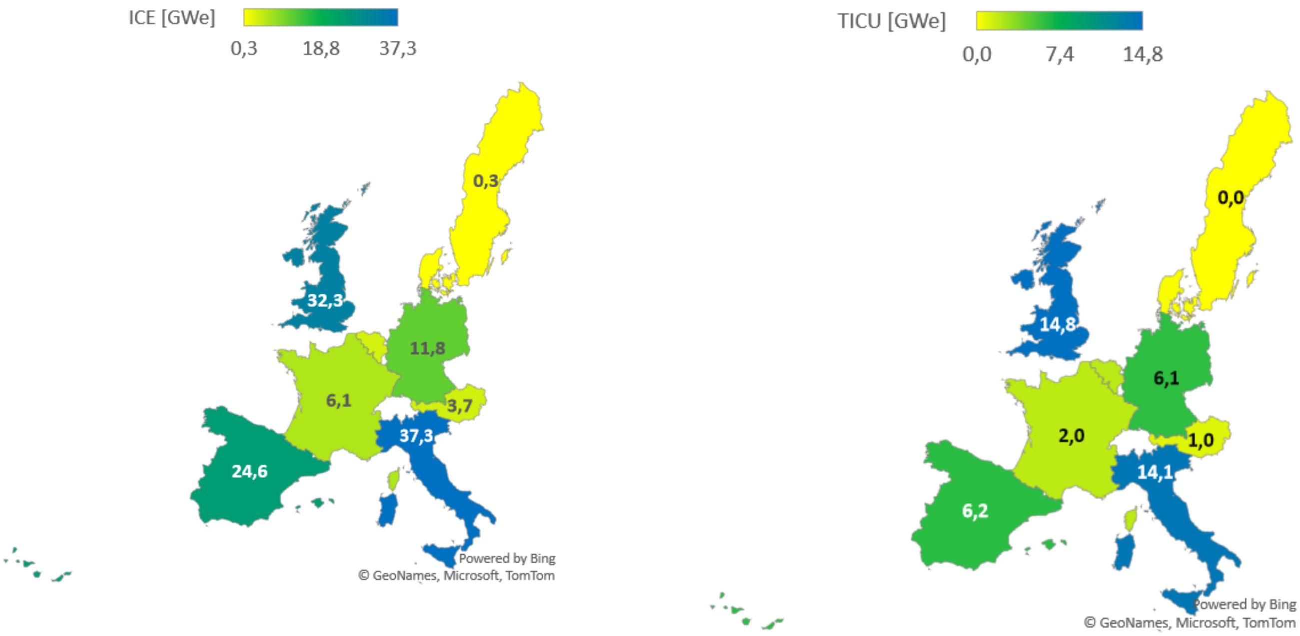

Figure 6: Replicability of flexibility provision from NPT case study (gas-fired plant) in the selected countries, left: units' number, right: temporarily installed capacity utilisation (TICU).

3 Aggregation and trading of MES flexibility

3.1 Aggregation of MES

The possibility for aggregators to participate in energy markets and trade flexibility services allows decentralised installations, not reaching the minimum bid size thresholds required for accessing the different markets, to participate. The participation in flexibility markets through a multi-energy aggregation platform can therefore increase the ability of MES to participate in electricity markets under the current regulation. More MES flexibility may be exploited through aggregation as other units in the aggregation pool may allow to fill the minimum bid size. However, aggregation will not bring any benefits for markets where the minimum bid size is very low, like the ID market (minimum bid size of 0,1 MW). For MES with large flexibility potential (e.g., ACS), aggregation is not essential either since these plants can reach the minimum bid size in ancillary services markets (where the thresholds are generally higher).

To enable aggregation and market participation of MES, access to historical energy consumption data of large numbers of distributed units together with corresponding seasonality and historical weather data, is very important to build accurate forecast tools. For example, it can be difficult to accurately forecast the operation of one heat pump unit, due to diverse factors impacting on its operation and the aggregation of a number of units can help to even out the diversity of individual units.

The simulation of aggregation and trading was performed for the case studies of Austria, Denmark, France, Italy, Spain, and Sweden. Flexibility providing units can earn different kinds of revenues in ancillary service markets. In general, there is a differentiation between capacity fees, that are paid for reserving the flexibility unit to be activated on request of the TSO, and activation fees, that are only paid for the activated energy, that was actually requested by the TSO. Capacity fees enhance the predictability of the revenues from ancillary service markets. But from the six investigated countries, capacity fees were only relevant in Austria. The revenues related to activated energy provision are difficult to predict, because the TSO's need for ancillary service delivery depends on the deviation of the grid frequency from 50 Hz, which follows a random distribution. In all investigated markets for ancillary services, the activated energy was less than 20% of the maximum possible energy provision, i.e. the product of reserved capacity times bid duration. As such, even if the TSO requires ancillary service provision, the demand may even be lower than the accepted capacity of the aggregation pool during some intervals. Additionally, even if the TSO requires ancillary service provision, bids of competitors may be cheaper in the TSO's merit order and the accepted capacity of the aggregation pool may not be activated at all or only partially, depending on its location in the TSO's merit order. Finally, non-energetic costs of energy (grid fees, taxes, etc.) must be taken into account when offering provision of negative flexibility.

In some markets for ancillary service provision, the flexibility provider will be penalized for underperformance, therefore there is an economic trade-off between trading the maximum amount of available flexibilities, which bears the risk of penalty payments, and a large amount of internal backup, which reduces the market revenues from flexibility provision.

The majority of project findings are market specific. Despite the ongoing harmonisation activities (e.g. PICASSO, MARI, FCR Cooperation) (ENTSO-E, 2021), the current very diverse structure of flexibility markets in the European internal electricity market does not allow the scaling/replicability of algorithms and business models. In addition, access to detailed information about market rules is often limited.

The majority of investigated case studies had clearly defined target markets, which showed an outstanding revenue expectation compared to the other investigated markets in the country. A dynamic change of the target market on daily basis was only investigated in the Austrian case. Simulation results show that as flexibility markets become more liquid, there is no clear priority of expected revenues between markets. Therefore, the dynamic switch between aFRR, mFRR and ID markets proved to be beneficial for the MES.

3.2 Flexibility services procurement mechanisms and aggregation

As mentioned above, the characteristics of the flexibility services in each country show that current market designs across Europe are widely diverse and driven by country-specific market environments. The main reason for differences in balancing market designs is the historical electricity mix. It will probably take years to fill the gap and fully open the markets to decentralized MES in all countries, with lighter and transparent pre-qualification processes. Additionally, in all countries, grid charges and requirements for aggregated behind-the-meter assets can be obstacles for MES to access the markets and for flexible consumption. Therefore, DSR is still mainly provided by large industrial plants, even if demand and batteries have a growing participation in different countries (e.g. Germany, Denmark) (SmartEn, Delta-EE, 2019).

Figure 7 shows the overall favourability of the current market designs and flexibility services procurement mechanisms to the participation of MES (yellow corresponds to least favourable, blue to most favourable). The results have been calculated using the ranking indications provided in each country report and the methodology proposed in MAGNITUDE Deliverable D1.4 (Pini, Seidelt, & Witkowski, 2020).

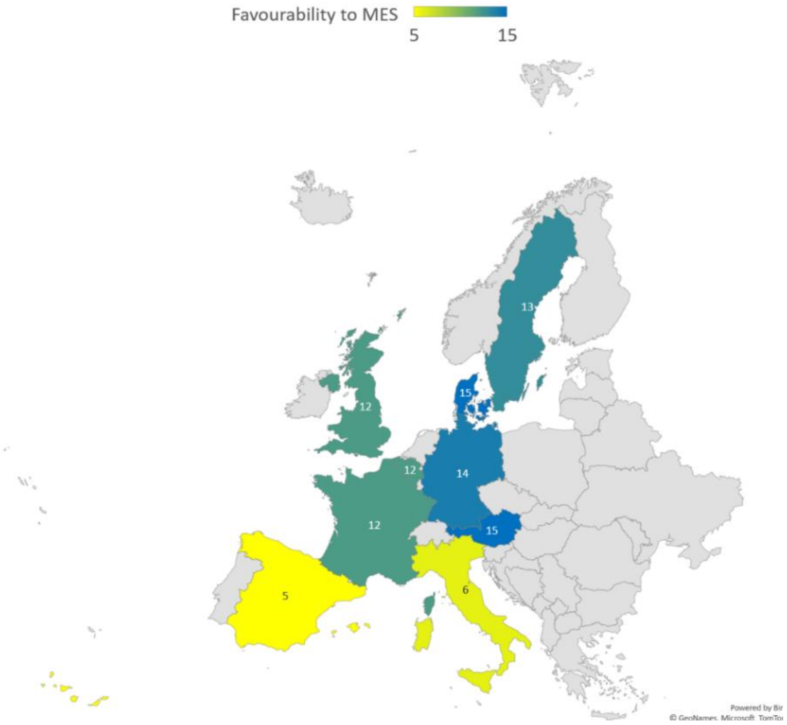

Figure 7: Favourability to the participation of MES in flexibility services procurement mechanisms and markets

Denmark and Austria are the two most favourable countries. All markets are technology neutral, with no price limits (except for DA, as in all the studied countries) and participation is voluntary for all services. However, no capacity requirement mechanism is available in either country, which is a limitation. In Denmark, DSR and aggregated generation can participate to all markets and (aggregated) load is also accepted in mFRR. 15-min products are available in ID. Very low minimum offer sizes are available in FCR and aFRR and procurement is done very frequently for all services. In Austria, DSR and aggregated generation can participate to all markets and (aggregated) load is also accepted in aFRR and mFRR. 15-min products are available in DA and ID (positive for small MES, providing heat to end customers and so limited in the fuel shift duration). Weekly procurement for FCR and aFRR (instead of daily or hourly, as in Denmark) can be a bottleneck or an advantage, depending on the current MES set-up.

Germany and Sweden follow closely. In Germany, DSR and aggregated generation can participate to all markets and (aggregated) load is also accepted in mFRR. All markets are technology neutral, except aFRR (no participation of variable RES) and mFRR (only wind turbines eligible among variable RES). There are generally no price limits, except in DA, ID and capacity reserve, and participation is voluntary in all markets. In Sweden, aggregated generation and DSR can participate to all markets – which is particularly relevant for MES with small installed capacities (e.g. Paris Saclay, HOFOR, EMUASA). Auctions are frequent and gate closing times are close to delivery – which is very important for MES supplying variable demand (e.g. ACS, Mälarenergi, Paris Saclay, HOFOR). Most constraints are in the technology’s eligibility: storage is not accepted in DA and ID, no RES can provide mFRR and only generators can participate to FCR.

Belgium, UK, and France present already favourable conditions. Markets in Belgium have undergone several changes in the last years, and reforms are still ongoing for the activation of a capacity reserve for the EU interoperability for aFRR and mFRR. Aggregation is allowed in all markets, except aFRR, but a new market design open to aggregation is under preparation. Some technology limitations are present in the access to aFRR (only large generators), but this is also object of reform. A new capacity reserve market will have its first auction in October 2021, to deliver capacity in November 2025. In the UK, DSR and aggregated generation can participate to all markets and (aggregated) load is also accepted in mFRR. Balancing services are currently procured through bilateral agreements.

In France, DSR and aggregated generation can participate in ID, DA, FCR and aFRR. They can also participate to mFRR under specific conditions (specific or dedicated mechanisms). The conditions will become even more favourable after the implementation of the PICASSO project in 2022. A capacity market exists, but the required availability for participants (10-24 peak days) can be a limitation for small MES, such as DH and DC networks.

Italy and Spain are currently facing several market reforms, but decentralised resources still have limited access to flexibility markets. Although the regulation, until 2017, was not favourable in Italy for MES, several changes happened since then and more are expected by 2025, which will make the market framework more open to flexibility provision than it is now. In 2017 aggregation and DSR were allowed through pilot projects (DG Energy, 2020). An ongoing reform will introduce continuous trading in ID, remove price caps from ID, DA and balancing markets Second generation of smart meters, allowing an updated reading at least every 15 minutes, are being deployed since 2016 and by 2025 more than 90% of customers and prosumers will be equipped with such devices, which will support the participation of small units.

In Spain, DSR and aggregated generation can participate only in DA and ID. FCR, aFRR and participation in capacity reserve are compulsory for eligible units. A capacity market is existing but inefficient and only open to traditional power generators. Reforms are ongoing through the participation of Spain in the MARI (mFRR) project. A derogation has been requested, on the other hand, in the PICASSO project (aFRR), to further develop national terms and conditions before implementation.

From a use case perspective, the provision of flexibility services from paper and pulp plants will probably give satisfactory results in countries where the minimum bid size is lower than in Austria, to ease direct market access, (aFRR: Belgium, Denmark, France) or higher demanded FAT, to put less stress on technologies (aFRR: Belgium, France; mFRR: Belgium, Italy, Spain). The participation of heat pumps, connected to a low-temperature DH network and supported by heat storage tanks, is replicable in all countries, with some current limitations in Italy, since the participation of aggregated DSR is only allowed, for now, in the framework of pilot projects. The availability of 15-min products in DA and ID (Austria for both, Spain, Sweden and UK for Intraday) is also an advantageous condition, since fuel shift from DH to heat production by heat pumps is more easily sustained for short periods. The provision of FCR, aFRR, mFRR by a CHP plant connected to a DH network, as in the case of ACS, is most favoured by higher FAT and, possibly, procurement close to service delivery, to ease heat production (Denmark, Germany, Sweden).

The replicability of a WWTP participating in ID and providing mFRR, is favoured where minimum bid size for mFRR is lower than in Spain, to ease market access (Austria, Belgium, Denmark, Germany, France), where non-symmetrical mFRR products are available, to provide negative or positive flexibility according to the demand’s needs, and where aggregation is allowed (all countries except, for now, Italy). The participation of CHP connected to a DHC network in DA, ID and mFRR, is more successfully replicable in countries with services procurement close to service provision, to ease scheduling of heat production (Austria, Denmark, Germany, Italy, Spain). Where the CHP is powered by biofuels, a high – compared to other countries - mFRR FAT can also be beneficial, as in Belgium, Denmark, and Italy (15 min, as in Sweden). There are no particular limitations preventing the participation of large gas-fired plants to flexibility markets.

Finally, aggregation of small distributed units such as, heat pumps and electric heat boosters can indeed be used to provide flexibility services to the electricity system. Ramping constraints might prevent such systems to participate in FCR, or aFRR. For these MES, the ID and mFRR markets will be more interesting, provided that the market liquidity is sufficient. Pilot projects that use real-time data would be needed to further assess the potential of these aggregations of distributed units to provide flexibility services to the power grid.

3.3 Aggregation as a tool for efficient energy integration

In their basic principles, aggregation platforms collect requests and signals from the electricity markets and/or the service buyers, aggregate the flexibility of the MES and propose offers/bids to the electricity markets and services buyers. The aggregator role is carried out by a so-called “deregulated” player, i.e. a player in competition with the other market participants. This role can be carried out by any such “deregulated player”, for instance a supplier, a Balance Responsible Party (BRP), a producer, or a separate player. Currently, from the case studies considered in MAGNITUDE, it appears that the aggregator role is very often carried out by stakeholders who are the suppliers and/or traders for the MES.

The results of the MAGNITUDE project have shown that, through aggregation, many of the technological and market barriers preventing the provision of flexibility services by MES can be overcome. Whether or not and to what extent aggregation can help address the barriers depends on the portfolio of units in the aggregation, on the performance of the corresponding communication and computation facilities, and on the optimisation and control strategies used.

As the energy system evolves towards a more decentralised system, involving a wide variety of actors, aggregation offers a viable and efficient way to ensure that all actors, regardless of size, can participate. As discussed, aggregation can allow decentralised multi-energy systems to come together and participate in all energy and service procurement market mechanisms, overcoming constraints related to size, timings, and capacity. This also applies to individual actors, in particular European citizens, who can come together to own and operate community energy projects as well as their own individual solutions. This requires active engagement with the grid operator and/or local utility to ensure this electricity is used as efficiently as possible.

4 Market and regulatory perspectives

4.1 Organisation and collaboration between stakeholders

The main stakeholders involved in the electric, gas, heating and cooling sectors carry out similar essential functions. The inherent physical characteristics of energy service provision mean that each sector involves generation, consumption, storage, and delivery of energy. The network or system must be operated by certain actors, and supply and demand must be balanced. These common requirements give rise to similar roles in each sector such as producer, consumer, transmission and distribution network operator (even if we mainly have distribution networks for the heat/cooling sector but transmission networks can sometimes be found like in the Copenhagen area in Denmark), balance responsible, supplier, storage provider, regulator, etc.

The similarity of the roles carried out by the actors in each sector presents an opportunity for increased cooperation as part of efforts to enhance the synergies between these sectors. Exploiting these synergies is key for the provision of flexibility services and the reliable operation of a highly integrated energy system.

However, the respective operational characteristics of the electricity, gas and heating/cooling networks are very different in terms of time constants, dynamic behaviours, resilience, and contractual obligations of their respective core business, so that their operation needs and requirements also differ considerably (Cauret, et al., 2019). Additionally, the professional culture and industrial philosophy within each sector has been built up over decades and widespread structural changes can face significant institutional inertia.

New frameworks and channels are needed to improve collaboration and transparency between different actors. **A coordinated and ambitious campaign, supported by education and training, is needed to increase awareness and build links between actors in the different sectors.** On a national level, as a starting point, knowledge sharing and networking events offer a viable and low-cost solution to begin the process of breaking down institutional silos. These events could be organised for instance by TSO or DSO representatives, to build contacts within the electricity, gas and heating/cooling sectors. To evolve towards a more collaborative, open working culture, future engineers and technicians should be educated on the merits of and need for cross-sector cooperation.

Generic sequence diagrams, such as those developed in the project (Belhomme, Raux-Defossez, Motte-Cortés, & Kessels, 2020), offer a useful tool to describe the organisation of the stakeholders in the different sectors, the links between them and the flexibility provision mechanisms. Stakeholder interactions can be scaled up, incorporating changing market dynamics, and used as the basis for cost and benefit analysis for elaborating the success of business models for different MES, in specific countries.

However, the characteristics of the electricity, gas and heat markets differ in terms of organisation, trading times and mechanisms, and product requirements. There is no unbundling in the heating/cooling sector and often no organised market, although some areas, such as Denmark, have DA and ID processes. Additionally, district heating and cooling makes up a small market share of the overall heating and cooling demand in most countries. In the electricity and gas sectors, despite harmonization initiatives, there is a large diversity of market mechanisms and rules.

Improved market designs integrating a cross-sectoral approach are needed to increase the synergies between the energy markets and enhance the participation of MES in these markets. **Innovative business models are also needed to promote and enable integration of different energy sectors.** These models should promote the provision of flexibility services and be favourable to all involved stakeholders.

4.2 Current status of energy markets and service procurement

When comparing different countries, national market designs for the electricity sector are more similar than those in the gas sector, while the organisation within the heating/cooling sector is inherently local and heterogenous. In the electricity system, the mechanisms for the provision of flexibility services and products show some consistency across Europe, consisting of the following three main phases:

- The planning and product procurement phase: identification of needs, submission of requests/bids, contract formulation.
- The product delivery phase: activating mechanisms, product physical delivery, monitoring.
- The settlement or post-delivery phase: exchange of metered data, financial settlement, remuneration, cost recovery, possible penalties.

The major processes for the day-ahead and intraday energy markets are already similar in the considered countries. The continuing efforts to harmonise and integrate national markets into a pan-European electricity system is a driving force for transnational trading, and energy market coupling and/or transnational trading platforms are already in place and operated.

However, a large diversity of mechanisms and rules for the provision of ancillary and balancing services is still observed across Europe (diversity of product definitions, auction or bid submission process, clearing mechanisms, etc.). Additionally, this is a fast-evolving field: some rules or mechanisms can change from one year to the other, or sometimes even faster. Due to this large market diversity between countries, the service providers (e.g. MES, aggregators) need to take into account the specificities of the three sectors both at national and local scales and closely monitor the evolutions of the regulatory frameworks.

4.2.1 Barriers

As mentioned above, the provisioning mechanisms and markets are still heterogeneous between the considered countries. Despite ongoing efforts to harmonize the market designs at European level, there is a large diversity of market mechanisms and rules. Some countries have exclusivity principles for participation in certain markets and in Sweden the provision of strategic reserve service prevents the participation in other markets.

Certain rules and requirements prevent/limit flexibility service provision by MES. There is still a non-level playing field regarding the participation in and access to energy markets. High thresholds (or minimum bid size) in some countries for the procurement of some services prevents MES participation and might even make it difficult for small pools of MES to participate. Aggregation is not yet fully allowed in some countries. Restrictions on some technologies also prevent them to provide ancillary services. Other barriers include the lack of liquidity in some European electricity markets (like intraday energy markets or mFRR in some countries), increased tariffs/taxes and an overall lack of coordination between network operators.

4.2.2 Overcoming market obstacles

Aggregation offers a viable way to side-step many of the market barriers preventing the participation of MES in different energy and ancillary service markets, although there are also some barriers that still cannot be overcome. In certain countries, aggregation is still excluded in certain key mechanisms such as the DA and ID energy markets or balancing and frequency regulation mechanisms. The removal of such barriers would allow aggregated MES to participate in all energy markets.

On a national level, grid tariffs, energy taxes and renewable support schemes need to be revised to reflect the evolution of energy markets. In cases where the current network tariffs, taxes or contractual clauses discourage the participation of flexibility-provisioning technologies, these should be revised, with the aim of supporting the integration of renewable electricity (while ensuring that the network costs are still properly recovered).

In the traditional energy system, energy was generated in large-scale centralized plants, and linearly transported to end-consumers, that occupied a passive role in the system. The inherent ramping capabilities and dispatchability of fossil fuel plants provided most of the necessary flexibility (along with hydro power plants and pumped storage), peak loads were easily covered by burning more fuel and participation to energy markets was restricted to big players. As we transition, towards a more dynamic, renewables-based system, a larger diversity of actors now plays increasingly important roles in the energy system. However, access to information or data, technical expertise, and capacity to enter the energy markets can all hinder the participation of these actors. Grassroots mobilization of local stakeholders can potentially allow MES to overcome some of these barriers. By engaging with local energy communities, local authorities and businesses, MES can become a driver for local energy transitions, allowing local communities to engage with, own and operate MES projects. An initiative to promote knowledge-sharing and success stories between MES on how to involve the local community and overcome some of the main barriers to participating in energy markets could enable projects across Europe to implement these solutions.

The ongoing harmonisation of the electricity markets across Europe is important and needed. Some mechanisms, e.g. the DA and ID electricity markets, are already similar in many European countries, transnational trading platforms already exist and harmonization initiatives of TSOs are in progress for balancing and frequency control services (FCR cooperation, PICASSO, MARI, TERRE).

4.3 Innovative market designs

Innovative market designs have been proposed to increase the synergies between the day-ahead electricity, heating/cooling and gas markets. In these "multi-carrier markets", the existence of physical and economic dependencies between the different energy carriers, which are currently not considered in the market products and the market clearing process, are explicitly taken into account to achieve the full potential of sector integration.

Five multi-carrier market schemes (described in Table 3) have been compared in the project and outline different levels of market integration and locality, with Market Scheme 1 (MS1) reflecting the benchmark of single carrier markets found across Europe today and Market Scheme 5 (MS5) reflecting the ideal scenario of a unified multi-carrier energy market. MS1 and MS5 were thus investigated in more detail.

Table 3: Overview of multi-carrier market schemes: scope, advantages, and disadvantages.

Market scheme	Scope	Advantages	Disadvantages
MS1: Single carrier energy market scheme	Separate day-ahead energy markets are organised for different energy carriers (i.e., gas, heat, electricity)	• Least effort to shift from the current situation. • Limited complexity in market clearing and product definition.	• Market participants with conversion technologies are exposed to more uncertainty. • Risk for unprofitable accepted bids / infeasible market outcome. • Not necessarily global maximisation of social welfare.
MS2: Mixed single and multi-carrier energy market scheme	Multi-carrier markets for gas, heat, and electricity at the local level. Single carrier markets for electricity and gas at the global level.	• Addresses the need for more energy system integration at the local level. • Still realistic shift from current situation. • Local economic multi-carrier system optimisation possible.	• Need for more complex clearing and order formats at local level. • More complex bidding system needed to generate multi-carrier orders. • More difficult to coordinate the interactions between local and global markets. • Local multi-carrier markets might be rather illiquid. • Not necessarily global maximisation of social welfare.
MS3: Coexisting global and local multi-carrier energy market scheme	Unique multi-carrier market for electricity and gas at the global level. Multiple local multi-carrier markets for heat, gas, and electricity at the local level.	• Linkages between carriers can be captured on the market at both local and global levels.	• Need for more complex clearing and order formats at both global and local levels. • More complex bidding system needed to generate multi-carrier orders. • More difficult to coordinate the interactions between local and global markets. • Local multi-carrier markets might be rather illiquid. • Not necessarily global maximisation of social welfare.
MS4: Local multi-carrier energy market scheme	Only local multi-carrier markets for heat, gas, and electricity.	• Linkages between carriers can be represented on the market at local level. • Depending on the implementation, market participants may have more autonomy.	• Drastically different from the current practice and evolution. • Need for more complex clearing and order formats. • More complex bidding system needed to generate multi-carrier orders. • Need for more complex communication/coordination between different local markets. • Local multi-carrier markets might be rather illiquid. • Not necessarily global maximisation of social welfare. • Lack of a system wide view.
MS5: Unified multi-carrier energy market scheme	One unique multi-carrier market for heat, gas, and electricity.	• Global maximisation of social welfare is possible. • Market Participants only need to consider one market for the different carriers.	• Need for more complex clearing and order formats. • More complex bidding system needed to generate multi-carrier orders. • High computational complexity.

The markets designed for MS5 contain new market order types (conversion orders, time-shifting orders) and constraints to alleviate market risks for traders caused by price forecasting errors of different markets. These new order types enable conversion and storage technologies to bid efficiently in the coupled energy carrier markets. Three different integrated multi-carrier DA markets with different organisational structures to explicitly include the underlying physical coupling between different energy systems were proposed. These structures largely resemble current European electricity markets and have the potential to deliver significant benefits in terms of social welfare, system resilience and RES integration. With further development and optimisation, these market designs may eventually eliminate the need for accurate price forecasts.

In energy markets today, imperfect forecasts can result in a loss of profit or opportunity for market participants, especially conversion technologies. Time shifting orders could be introduced in single-carrier markets, even if market-based energy sector integration is not further exploited. They leverage the full flexibility potential of technologies with limited energy content such as demand-side flexibility or storage better than the current order types in the European markets.

The multi-carrier market framework developed within MAGNITUDE can be used in two ways:

- As a benchmark for a perfect integration of DA multi-carrier energy markets (e.g. as a framework to conduct quantitative analyses on sector coupling potential at the European level).
- To assess the value of introducing a new technology (including conversion or storage technologies) in the existing DA markets.

This framework can address the need for a coordinated, market-based energy system integration, to enable the decarbonisation of different energy sectors, by increasing the flexibility and resilience in the operation of underlying energy systems and improving the economic efficiency of the related energy markets. This need has been described in the EU Strategy for Energy System Integration (European Commission, 2020b) and the outputs of the MAGNITUDE project go a long way in beginning to meet this need.

During the project, two multi-carrier DA market designs were simulated using the Northern Italy market zone and considering the assets of the multi-energy system of the ACS case study in Milan:

- A decoupled (sequential) multi-carrier market design with decentralised clearing (based on MS1).
- An integrated (coupled) multi-carrier market with centralised clearing (based on MS5).

Coupled multi-carrier markets can better deal with situations when supply limits in any of the energy carriers are being reached. The analysis of differences per technology level (gas boiler, CHPs, heat pumps) indicates that for a typical summer and autumn week, all the technologies have a better net surplus under the coupled market design. In a winter week, it was shown that the coupled market design, due to its capacity for a more precise storage and conversion technology integration, performs significantly better than the sequential market. Higher welfare levels are achieved with coupled markets, as they better represent and take into account the techno-economic characteristics of conversion and storage technology owners in the market-clearing. As coupled markets mitigate trading risks related e.g. to market price forecast errors, they ensure that market parties obtain the best profits, besides leading to more meaningful price signals. The coupled multi-carrier market design is very suitable for the mitigation of technical (operational) and economic (loss of profit) risks coming from the price forecasts in sequential markets. Multi-carrier markets are hence better suited for dealing with uncertainty, avoiding technical infeasibilities, and incorporating more flexibility in the system (e.g. DSR flexibility, or flexibility for which due to the forecast errors there is no economic rationale for activation).

The project results indicate that market-clearing of coupled markets takes longer than sequential market-clearing. The size of the coupled multi-carrier market-clearing problem increases compared to the single market-clearing, and this is expected to increase the computational time. This aspect should be further investigated to confirm if it is still within reasonable margin for practical implementation. Coupled markets generally enable matching more volumes for all the energy carriers. This is essentially the consequence of incomplete information of market participants in sequential markets and forecast errors leading to uninteresting bids which are finally rejected in sequential markets but which correspond to technologies whose conversion or storage orders would have been accepted in coupled markets. There are minor deviations for heat delivery in winter weeks, which could be a consequence of the gas scarcities in those weeks as explained above. From a renewable energy perspective, the multi carrier market enables a better representation of cross carrier or temporal flexibility in the market-clearing process through the utilisation of the novel constraints and order types (conversion, time shifting orders, pro-rata constraint) and hence, automatic scheduling of such flexibility in the DA markets. This is expected to reduce the variable RES curtailment and promote their integration.

The main conclusion is that the integrated multi-carrier markets can better deal with forecast errors, can better deal with shortages, and should more easily integrate renewable energy sources than the decoupled markets. The above-listed benefits come at the price of higher computational times for calculating market-clearing outcomes of coupled multi-carrier markets compared to sequential markets. The additional trade-off is in the increased complexity and increased information shared by the market parties with the central market-clearing operator due to the nature of the novel order types and constraints, which enable sharing more techno-economic constraints of the underlying portfolio or the technology, such as conversion efficiency.

The above market design schemes result from a conceptual analysis carried out by the MAGNITUDE project. A more detailed comparison integrating cost-benefit analyses, taking into account not only the implementation costs of such market designs but also the impact on the transaction costs, is needed to further develop and scale up these designs. A thorough understanding of the impact on all involved stakeholders is required before considering any real-life implementation.

The outcomes of the MAGNITUDE project show that there is a value in a more coordinated market-based operation of different energy sectors. The value is related to higher economic efficiency, better integration of RES, and higher system resilience. Nevertheless, to achieve this value through common operation of DA markets of different vectors, further investigation is needed on the benefits of:

- increased competition in the heating and cooling sectors, including cost-benefit analyses of the implementation of a more market-based approach in the district heating and cooling sectors,
- a better alignment of the gate-closure times of the current markets of different energy vectors
- the introduction of new order types like the time-shifting orders in the existing electricity markets, to enable technologies with limited energy content to participate in the market more easily, and as such increase the flexibility in the system
- the exploitation of synergies among energy vectors at a local level (e.g. on a district level, or within an industrial area).

In MAGNITUDE, we focused mainly on the merging of market operators of different energy vectors, or on their close cooperation, during the DA market clearing. However, there are other possibilities for coordination, in terms of information exchange, that should still be further explored. To this end, additional support for research and the accompanying pilots are needed on the different forms of market-based integration of energy vectors.

Regulatory sandboxes should be encouraged to implement and test new multi-carrier market concepts, improved flexibility procurement mechanisms and market-based energy sector integration concepts in real-life.

5 Energy System Integration through MES

As mentioned in (European Commission, 2020b), the European "*energy system is still built on several parallel, vertical energy value chains, which rigidly link specific energy resources with specific end-use sectors*". The system is still highly dependent on fossil fuel imports from countries with increasingly unpredictable geopolitical environments, making it vulnerable to external shocks. This siloed system of separate markets and independently planned and managed networks is "*technically and economically inefficient*" and cannot contribute to deliver a climate neutral European Union by 2050. Multi-energy systems offer a technically efficient and economically viable solution that can provide a source of flexibility to the electricity system and balance to the future integrated and highly optimized energy system.

"*Energy system integration – the coordinated planning and operation of the energy system 'as a whole', across multiple energy carriers, infrastructures, and consumption sectors – is the pathway towards an effective, affordable and deep decarbonisation of the European economy in line with the Paris Agreement and the UN's 2030 Agenda for Sustainable Development*." (European Commission, 2020b). MES epitomize this strategy and should be promoted as effective, decentralized resources to deliver climate neutrality.

5.1 District Heating and Cooling

Heating and cooling account for half of total final energy consumption, with over 70% of this energy coming from fossil fuels. DHC is a cost-effective, future-proof solution for the decarbonisation of the heating and cooling sector and the energy system as a whole. DHC connects the local level with EU level electricity and gas infrastructures and offers energy storage to contribute to the balancing of supply and demand. Heat networks deliver energy efficiency (through the use of CHP and recovery of waste heat), facilitate the integration and storage of intermittent renewable electricity and gas and provide a link between a wide range of local sources of heat or cold and the buildings in which they are needed, particularly in cities.

DHC systems are the ideal backbone for a highly integrated energy system. Sector integration through DHC systems enables the integration of variable renewable electricity and maximises the recovery and utilisation of locally available waste heat sources from both industry and unconventional sources (tertiary buildings, supermarket refrigeration, underground metro stations, data centres). Modern low-temperature heat networks should be promoted, as they can connect local demand with renewable and waste energy sources, as well as the wider electric and gas grids – contributing to the optimisation of supply and demand across energy carriers.

District cooling (DC) is a key technology for addressing Europe's increasing demand for cooling. DC is highly energy efficient compared to equivalent conventional systems and also contributes to sector integration by utilising waste heat, ambient energy and geothermal energy to meet demand for cooling, reducing the strain on electricity grids and mitigating the heat island effect in cities.

5.1.1 Technologies Enabling Flexibility Provision by DHC

DHC networks provide flexibility through the means of technologies which are already both technically and commercially available. Much of the heat supplied to DHC networks across Europe is produced in highly efficient CHP plants. As previously mentioned, gaseous fuels provide greater flexibility when compared to solids ones. Cogeneration is a long-established source of flexibility and is a perfect example of the benefits delivered by integrating different energy sectors. To maximise this flexibility, markets should be adjusted to ensure that CHP can take part in capacity mechanisms. Large heat pumps are readily available but face market design barriers due to the taxation of electricity. The integration of large heat pumps in DHC networks provides a link between the electricity and heating and cooling sectors that enables flexibility provision via load shifting. This integration constitutes a more efficient use of electricity when compared with individual, building-level heat pumps. Biomass and electric boilers are increasing popular technologies that can be used for meeting heat demands and provide flexibility. The capacity of electric boilers can be increased independently of the grid, by combining them with local thermal storage.

Waste heat recovery is a prime example of the circular approach that underpins energy sector integration. DHC systems provide the necessary infrastructure to utilise the potential of waste heat. The EU produces more waste heat than the demand of its entire building stock. Industrial emissions currently make up about 21% of EU GHG emissions. The energy efficiency of the sector can be improved through the recovery of waste heat. Recovered heat not consumed within the plant can be fed into heat networks and consumed externally, either in another plant within an industrial cluster or as space and water heating for buildings. Heat Roadmap Europe estimate that industrial waste heat could cover at least 25% of district heating generation. Moreover, there is significant heat recovery potential from unconventional waste heat sources (e.g. sewage water, supermarket refrigeration). These unconventional sources of waste heat are most often located in urban areas. Demand for heating and cooling is highest in these areas and so DHC networks are well placed to provide the link between this supply and demand. Approximately 1.2 EJ (or 340 TWh) per year could be recovered from data centres, metro stations, service sector buildings, and waste-water treatment plants. This corresponds to more than 10% of the EU's total energy demand for heat and hot water (approximately 10.7 EJ or 2,980 TWh) (EHP, AIT, 2020).

5.1.2 Barriers to DHC

The barriers preventing DHC from maximising its potential to contribute to sector integration are market-related and political in nature. Many of these barriers could be addressed at EU level, including with the implementation of the Electricity Market Design Directive (European Union, 2019b). One of the main market design barriers, which applies to most EU countries, is that electricity used in power-to-heat applications is considered and taxed as end-used electricity, which makes this solution uncompetitive, especially when compared to natural gas. Taxation of electricity makes it difficult for operators to consider investing in power-to-heat facilities. More broadly speaking, the Energy Taxation Directive must be reviewed and fully updated with the Green Deal ambitions.

The lack of a local/district approach to energy planning is a barrier to the development of DHC. Absence of a systematic local energy planning prevents local stakeholders from linking their mapping and planning for available energy supply (in virtue of article 14 of the Energy Efficiency Directive) with buildings renovation strategies (according to article 2 of the Energy Performance of Buildings Directive). This is a missed opportunity for identifying potential synergies that can emerge between local energy markets (for heat, electricity and gas production) and the building stock.

There is no tax on the carbon content of fossil fuels used in individual heating solutions, in most countries. While gas is cheap, electricity is heavily taxed. However, a tax reduction for electricity could potentially be harmful to the DHC sector, favouring individual solutions such as individual heat pumps. There should be a level playing field for all flexibility solutions. The support for renewable electricity is paid for a part from CO_2 revenue, and so ultimately it is paid by consumers. Member States should be encouraged to support RES for heat and not only renewable electricity, through state aid. A large share of the heat in district heating systems is generated in cogeneration plants, producing both electricity and heat from either fossil fuels or renewables. However, due to low prices paid for generated electricity in most of the European countries, many CHP operators are facing some big financial losses. Appropriate remuneration for the provision of flexibility services is needed.

There are also political barriers that are holding DHC back. The policy narrative places a large emphasis on the role of electricity and gas in the energy transition, in particular hydrogen, leaving the heating and cooling sector to the margins of the debate. Although this is becoming less the case in recent years, the fact that heating and cooling account for half of all energy consumption cannot be ignored. The multiplication of gas infrastructure is inefficient. Increased dialogue and cooperation between the different energy sectors is needed, beyond the formal exchange between ENTSO-E and ENTSO-G. The approach to large infrastructure investments should be systemic, transparent and consider the cheapest option available. Legislation must prioritise rapid deployment of renewable heating and cooling technologies in order to meet the 2030 and 2050 climate and sustainable energy targets.

5.1.3 Policies to Promote Flexibility Provision by DHC

The heating and cooling sector will play a pivotal role in making Europe the world's first climate neutral continent. DHC is a proven technology that offers a pathway to realising this ambition by enabling sector integration. At European level, models, investment policies and funding instruments need to integrate the concept of sector integration and fully address the development of DHC networks.

Electrification will play an increasingly important role in supplying end-use heat and cold demands in the coming years. Large-scale heat pumps and electric boilers can supply heating/cooling or upgrade waste heat to a suitable temperature in a cost-efficient and environmentally friendly manner, when supplied by renewable electricity. The integration of these technologies offers a more efficient use of electricity when compared to building level installations. Through the closer integration of the power and heat sectors, electric heat appliances could already make use of real time electricity prices to smarten DSR. The integration of power-to-heat systems combining large-scale heat pumps, electrical peak-load boilers, storage and CHP into DHC systems offers a cost-effective and energy efficient pathway for the electrification of heating and cooling.

The recovery of waste heat offers a readily available source of primary energy savings and exemplifies the circular and collaborative approach of energy system integration. DHC systems provide the necessary technology to capture the potential of waste heat. The recognition of the sustainability of waste heat projects in the EU taxonomy is a positive and encouraging signal. Waste heat recovery projects have high CAPEX and financial risks. They require a long-term commitment that is sometimes not compatible with the constraints associated with the development and operation of industrial sites.

There are barriers at member state level, but certain actions taken at EU level can overcome some of these barriers. The utilization of waste heat within local, regional, national and European energy efficiency, supply and decarbonization strategies should be supported. The identification and access to information on waste heat recovery potential and sources is key, for instance the work carried out by Member States under the Energy Efficiency Directive article 14 Comprehensive Assessment or EU funded projects creating open source databases of waste heat sources. These analyses will need to translate into national strategies and concrete measures to support waste heat recovery as an integral part of decarbonisation.

A better dialogue between governance levels and stakeholders is necessary to ensure the planning and implementation of waste heat recovery projects and provide the possibility to the local level to showcase best practices. The recovery of industrial waste heat is an opportunity to develop new infrastructure, for instance in industrial areas where heat can be supplied to/shared by different users. Such developments will represent a new source of revenue for producers while providing affordable and sustainable heat for users. Waste heat not consumed within industrial parks can be supplied to nearby buildings through DHC networks, contributing to the decarbonisation of local heat supply.

Support for thermal energy storage (weekly and seasonal, small- and large-scale) is essential to maximise the flexibility potential of this enabling technology. Flexible heat prices would benefit providers of thermal storage and incentivise further uptake. Additionally, the roll out and enlargement of modern, low-temperature DHC networks is required to maximise the benefit of highly efficient P2H technologies, in the form of large-scale heat pumps.

5.2 Gas

Gas-fired units are very useful for meeting peak demands, providing greater flexibility when compared to solid fuels. Gas-fired cogeneration offers a huge source of flexibility, linking the heat and power sectors. Renewable gases are expected to play an important role in the future, especially in applications where direct heating or electrification are not feasible; while natural gas will likely represent an important bridging technology as the energy system transitions towards decarbonised supply. Renewable gases such as those produced from biomass, or green hydrogen can offer valuable solutions to exploit energy produced from variable renewable sources, developing synergies between the electricity sector, gas sector and end-use sectors.

Smart sector integration must be technology-neutral and driven by commercial and environmental choices.

The Ten Year Network Development Plan (TYNDP) (ENTSOG, 2021) provides an overview of the European gas infrastructure and its future developments, and also includes a European supply adequacy outlook and an assessment of the network resiliency. The planning of electricity and gas networks should be transparently coordinated at national and EU level, and linked to heat network development at local level. The increased tendency towards decentralisation of the energy system, means that distribution system operators will take on a more prominent role in the planning and market coordination of decentralised sources. Incentives should be provided for the development of local biogas networks, especially in rural areas.

Hydrogen has the potential to provide energy to sectors that are not suitable for direct electrification and offers a valuable storage option for variable renewable electricity. As part of a highly integrated energy system, hydrogen can support the decarbonisation of industry, transport, power and buildings across Europe, as outlined in the EU Hydrogen Strategy (European Commission, 2020a).

5.3 Electricity

There is broad consensus that energy system integration involves the coordinated planning, integration and operation of the electricity system and various other interacting energy sectors. The electrification of a large share of our energy consumption can cut primary energy demand by a third due to the efficiency of electrical end-use technologies (European Commission, 2020b). This combined with the rapid growth and cost competitiveness of renewable electricity production presents a strong case for the electrification of other end-use sectors e.g. supplying space heating using heat pumps, electrification of transport vehicles. This penetration of renewable electricity into hard-to-abate sectors will provide valuable reductions in GHG emissions. A highly integrated system, involving a wider variety of actors will act as a multi-directional system. Consumers will actively engage with their energy consumption, with decentralised actors such as MES providing valuable flexibility and balancing services to the system. A network approach should be adopted to facilitate the development of multi-energy technologies and their interaction to optimise system operation while ensuring maximum benefits for the environment. This should be reflected in the TYNDP, produced for the European electricity and gas sectors, by ENTSO-E and ENTSOG, respectively (ENTSO-E, 2021) (ENTSOG, 2021). The energy transition requires a multitude of solutions coming from all energy professionals and users. In line with the approach adopted by the MAGNITUDE project, TYNDP should also integrate heat networks where possible to exploit the synergies between the electricity, gas and heating and cooling sectors.

The EU Electricity Regulation and Directive (European Union, 2019a), (European Union, 2019b) provide the basis for an ambitious European Green Deal and Green Recovery. Dynamic coordination of different energy markets is needed if Europe is to realise its climate targets in a cost-effective manner. To date, there has been limited progress on the implementation of demand-side flexibility provisions in European markets. The market-based procurement of services from all kinds of Distributed Energy Resources (DER) by System Operators is still at its infancy and there are widespread limits to the non-discriminatory participation of DER in all markets and mechanisms (SmartEn, 2020).

A definition of Demand Side Flexibility (DSF) is provided in (SmartEn, Delta-EE, 2021) as "*Decentralised behind-the-meter sources of flexibility are collectively termed Demand Side Flexibility (DSF). DSF is technology agnostic and refers to the turning on / off, up / down, or shifting of, decentralised loads, batteries and generation across any value stream or customer segment. Assets can be aggregated or utilised individually*". There is DSF activity in varying degrees in markets across Europe. In 2020, more ancillary services have opened to DSF, with DSO-specific products emerging. Industrial customers are the most active, with aggregators acting as market creators. France and Great Britain are the highest-ranking countries for market activity, followed by Ireland, Germany and the Netherlands (SmartEn, 2020).

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