D7.3

MAGNITUDE lessons learnt

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D7.3 – Lessons learnt

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Executive Summary

The present report is the public Deliverable D7.3 of the MAGNITUDE H2020 European project. It is dedicated to the capitalization of the main outcomes and lessons learnt from the MAGNITUDE project and its seven real-life case studies, as well as to the description of identified or potential barriers and recommendations.

The MAGNITUDE project has developed a whole chain of optimization and coordination tools, as well as business and market mechanisms, to provide flexibility to the European electricity system, by optimizing the synergies between electricity, gas, heating and cooling systems.

More specifically, MAGNITUDE's main goals were to:

- enable the provision of services by Multi-Energy Systems (MES) to support the cost-effective integration of Renewable Energy Sources (RES), and enhance security of supply,
- bring under a common framework, technical solutions, market designs and business models,
- contribute to the ongoing policy discussions in the energy field.

The methods and tools developed in the project were assessed on seven real-life case studies of multi-energy systems of different sizes and technological features located in seven European countries (Austria, Denmark, France, Great Britain, Italy, Spain, and Sweden) and covering different regulatory frameworks, sector-coupling technologies, stakeholders and business models.

The overall MAGNITUDE approach to achieve its goals can be summarized by the following activities that were carried out and generated the project main results:

- Identify the most relevant flexibility services to be provided by Multi-Energy Systems (MES) to the electricity system, which allow to increase the share of RES and enhance security of supply, and characterize the procurement mechanisms for these services in the 7 case study countries.
- Characterize the main stakeholders involved in the electricity, gas, heating and cooling sectors, their roles and their interactions, and elaborate the MAGNITUDE technical and commercial functional architectures.
- Investigate the technologies and MES involved the seven real-life case studies considered in the project and study their actual capabilities to provide flexibility to the electricity system.
- Develop models and tools for the simulation and optimization of the control strategies of the technologies and MES in the case studies to improve their operation and maximize the flexibility provision.
- Develop an aggregation platform to quantify the benefits of pooling flexibilities of decentralized MES for trading on the identified energy and ancillary service markets.
- Propose and compare innovative market designs for the enhancement of the synergies at the level of the electricity, gas and heat markets, and implement them on a market simulation platform.
- Assess the integrated system (namely MES optimisation, pooling through the aggregation platform, and market simulation) for selected business use cases in the 7 case studies.
- Investigate the replicability and transferability of MAGNITUDE's business cases.
- Evaluate the business models for the MES operator and for the aggregator in the 7 case studies.
- Develop the specifications and a light implementation of a multi-energy data hub and interoperability layer.

- Propose policy strategy and recommendations in a pan-European perspective – including technology, market, business models, and regulation aspects, and spread the project achievements towards stakeholders in the electricity, gas and heat sectors to raise awareness and foster a higher collaboration.

The project results confirmed that MES can definitely provide flexibility to support the integration of RES in the electricity system and to contribute to decarbonization of energy system. MESs have potential to participate in energy markets, frequency ancillary service procurement, congestion management and capacity requirement mechanisms. But this strongly depends on technologies involved in the MES, the process and operation strategies.

The simulations carried out for the seven real-life case studies showed that a significant amount of flexibility can be available but only a small part of the available flexibility is actually activated (i.e. in terms of energy delivered). This is illustrated in Figure 1 which gives for each case study the average percentage of the available flexibility which is activated.

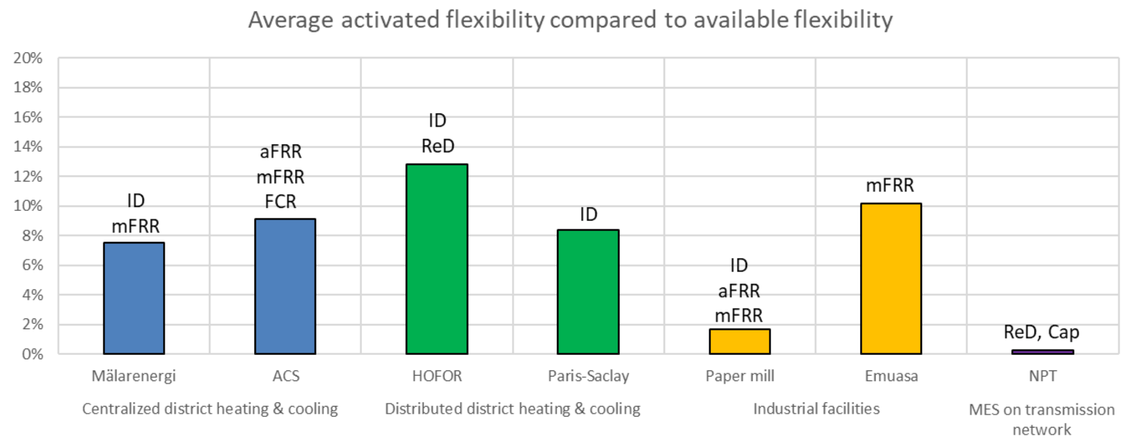

Figure 1 – Average activated flexibility in percentage of available flexibility

The main reasons for this situation are of different natures:

- Technical, for instance linked to the capabilities of the MES technologies to meet the requirements of the market products.
- Economic, for instance linked to competitiveness of the bids proposed on the markets with respect to other resources, or the economic viability of the business models.
- Regulatory, for instance linked to limitations to access some markets.

The main outcomes and lessons learnt of the project are explained in this deliverable, in which the following aspects are covered in detail:

- Provision of flexibility by multi-energy systems (MES),
- Aggregation of MES for flexibility trading.
- Market and regulatory perspectives.
- Replicability of the investigated use cases.
- Assessment of the business models of the MES operator and the aggregator.
- Stakeholders' roles and interactions, multi-energy data hub and interoperability layer.

Finally, the remaining challenges and future work are also described in a dedicated chapter as well as recommendations for further research and development activities, and future demonstration projects.

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List of Acronyms

Abbreviation/ Acronym	Description
ACS	A2A Calore e Servizi
aFRR	automatic Frequency Restoration Reserve
ANN	Artificial Neural Network
AP	Aggregation platform
API	Application Programming Interface
BM	Business model
BRP	Balance responsible party
BUC	Business use case
Cap	Capacity requirement mechanism
CAPEX	Capital Expenditure
CBA	Cost-benefit analysis
CCGT	Combined-Cycle Gas Turbine
CHP	Combined Heat and Power
CKAN	Comprehensive Knowledge Archive Network
COP	Coefficient of Performance
CS	Case Study
csv	comma separated values
DA	Day Ahead energy market
DER	Distributed Energy Resource
DH	District Heating
DHC	District heating and cooling
DHN	District Heating Network
DR	Demand Response

Abbreviation/ Acronym	Description
DSM	Demand Side Management
DSO	Distribution System Operator
DSR	Demand-Side Response
DWH	Domestic Hot Water
EBIT	Earnings before interest and taxes
EC	European Commission
EES	Electrical Energy Storage
EHB	Electric Heat Boosters
EMS	Energy Management System
EU	European Union
FAT	Full Activation Time
FCR	Frequency Containment Reserve
FI-PPP	Future Internet Public Private Partnership
GE	Generic Enabler
GHG	Greenhouse gas
H2P	Heat to Power
HP	Heat Pump
ICT	Information and Communication Technology
ID	Intraday energy market
IoT	Internet of Things
IRR	Internal rate of return
KPI	Key Performance Indicator
LTDH	Low Temperature District Heating network
LV	Low Voltage
MC	Multi-Carrier

Abbreviation/ Acronym	Description
MD	Market Design
MES	Multi-Energy Systems
mFRR	manual Frequency Restoration Reserve
MS	Market Scheme
MV	Medium Voltage
NPT	Neath Port Talbot
NGSI	Next Generation Service Interface
OCM	On-the-day Commodity Market
OTC	Over The Counter
OPEX	Operational expenditure
P2H	Power to Heat
P2X	Power to X
PV	Photo-voltaic
ReD	Re-dispatching mechanisms or active power control
RES	Renewable Energy Sources
RR	Replacement Reserve
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TSO	Transmission System Operator
UC	Use case
UK	United Kingdom
WP	Work Package

1 Introduction to the MAGNITUDE project

The present report is the public Deliverable D7.3 of the MAGNITUDE H2020 European project. It is dedicated to the capitalization of the main findings and lessons learnt from the MAGNITUDE project and its seven real-life case studies, as well as to the description of identified or potential barriers and recommendations.

1.1 Context and objectives of the MAGNITUDE project

The European energy system will experience important changes, in particular due to the targets set for renewable energy integration, reduction of greenhouse gas emissions and energy efficiency. Evolutions like the electrification of energy end-uses (e.g., development of electric vehicles, electrification of heating) will also have a significant impact.

In this context, the electricity system is expected to be exposed to new or increased risks, for instance in terms of quality and security of electricity supply, congestion, system stability, curtailments, difficulty to meet the demand at some periods of time (system adequacy). To face these risks, different studies show that there is a growing need for more flexibility and a more active involvement of all the stakeholders at all levels (from small consumers on the distribution network to pan-European networks) to ensure an efficient and reliable operation of the electricity system. The service provision capabilities of both centralized and decentralized resources in a coordinated way (including consumers' and producers' resources) will have to be harnessed.

Enhanced synergies between different energy carriers appear now as a possible means to provide flexibility to the electricity system, as well as to drive efficiency and business innovation in the energy sector. This is the topic of the Horizon 2020 European project "MAGNITUDE".

The project has developed optimization and coordination tools, and business and market mechanisms to provide flexibility to European electricity system by optimizing the synergies between electricity, gas, heating, and cooling systems. More specifically, MAGNITUDE's main goals are to:

- enable the provision of services by Multi-Energy Systems (MES) to support the cost-effective integration of Renewable Energy Sources (RES) and enhance security of supply,
- bring under a common framework, technical solutions, market designs and business models,
- contribute to the ongoing policy discussions in the energy field.

The methods and tools developed in the project are assessed on seven real-life case studies of multi-energy systems located in seven European countries (Austria, Denmark, France, Great Britain, Italy, Spain, and Sweden) and covering different regulatory frameworks, sector-coupling technologies, stakeholders and business models.

1.2 MAGNITUDE concepts and approach

The main concepts and high-level architecture of the MAGNITUDE project are shown in Figure 2 below [1].

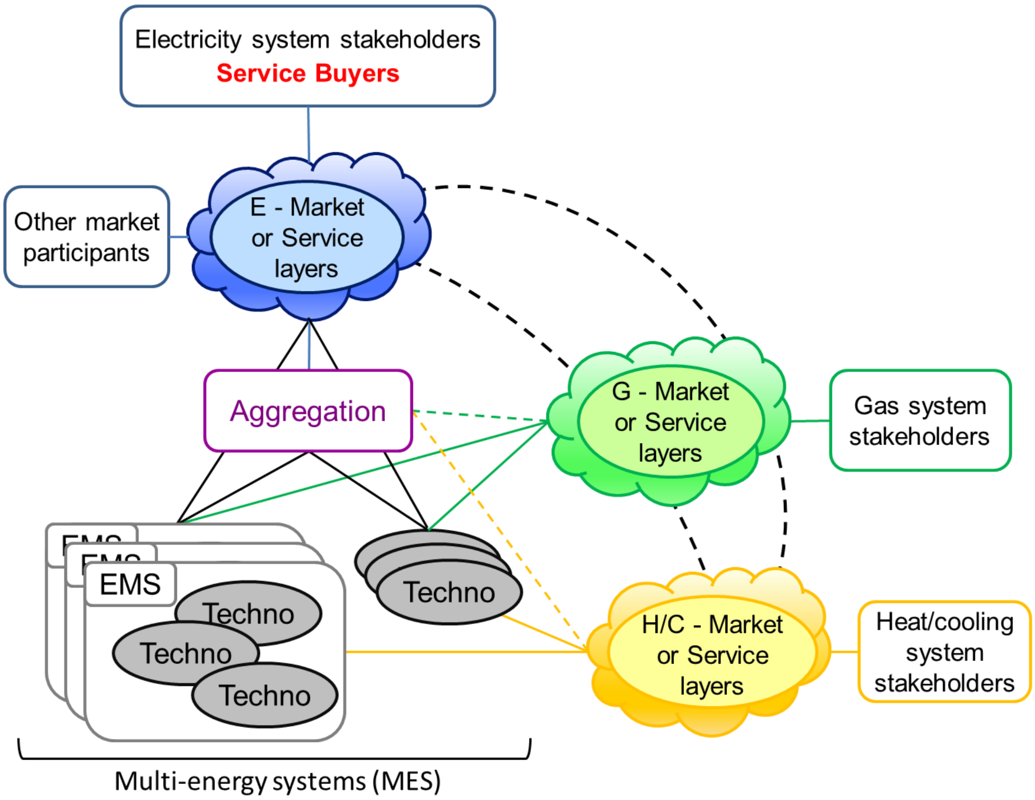


Figure 2 – MAGNITUDE concepts and high-level architecture [1]

In this conceptual high-level architecture,

- **The Multi-Energy Systems (MES)** are the providers of flexibility through the control of their technological components and the optimisation of their operation. As described later in Chapter 2, they may have different purposes and include different types of technologies and energy carrier networks (electricity, gas, heating, cooling). Depending on the case and on their size, these technologies can be in a large (industrial, commercial, or public) site or distributed at consumers' or prosumers' premises. They may also be operated through an Energy Management System (EMS) or an equivalent device, which can perform a local aggregation at the level of the site. Considering the voltage frontiers between transmission and distribution electricity grids in the considered countries, the considered MES are mainly connected to the distribution networks.

- **The aggregation platform (AP)**:
    - collects the requests and signals from the electricity markets (E-market) and/or the service buyers,
    - aggregates the flexibility of the MESs and integrate it in its portfolio of resources,
    - proposes offers/bids to the electricity markets and services buyers.

  For these purposes, the AP performs forecasting of market prices and of the flexibility of the resources in its portfolio, and carries out optimizations at portfolio level, both for the preparation of the bids and the optimal dispatch between the MES and the other resources in its portfolio. The aggregation platform is described in more details in Chapter 3.

  The aggregation 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.

- **Electricity market (E-market) or service layers**: all type of commercial relationships should be considered: organised markets and organised procurement mechanisms, call for tenders, bilateral negotiations or Over The Counter (OTC) trading, etc. However due to limitations of access to available data, mainly organised markets and mechanisms and some calls for tenders are studied in detail in the project.

  The electricity markets or service procurement mechanisms are composed of different layers, each associated with specific services and products traded. The following services have been selected as most relevant for MAGNITUDE's targets [2]:
  - provision of reserves for Transmission System Operators (TSOs): Frequency Containment Reserve (**FCR**), automatic Frequency Restoration Reserve (**aFRR**), manual Frequency Restoration Reserve (**mFRR**), and some dedicated additional balancing mechanisms which may exist in certain countries,
  - re-dispatching mechanisms or active power control for congestion management at both transmission and distribution levels (**ReD**),
  - energy procurement mechanisms and markets: day ahead energy market (**DA**), intraday energy market (**ID**),
  - capacity requirement mechanisms (**Cap**), such as capacity markets and strategic reserves.

  They are described in more detail in Chapter 4.
- **Gas and heat/cooling markets (G-Market and H/C-Market) or services layers**: in MAGNITUDE, the gas and heat/cooling markets or services provision mechanisms are not studied in full detail but are mainly considered to the extent that they affect or are affected by the MES provision of services to the electricity system. Indeed, the MES stakeholders procure or provide heat, cooling and/or gas and may also provide services to the gas or heat systems. The resulting potential constraints/barriers and opportunities/benefits have to be taken into account. They are described in Chapter 4.
- **Integrated (or coupled) multi-carrier markets**: innovative market designs are proposed and assessed for integrated/coupled multi-carrier markets, which allow to increase synergies between the electricity, gas, and heat markets. This activity focussed mainly on the design of day-ahead multi-carrier energy markets but could also be extended to the intraday energy markets. These innovative market designs are described in Chapter 4.
- **Multi-energy data hub and interoperability layer**: a large number of stakeholders are involved in multi-energy systems, and the exchange of information is becoming an increasingly complex and resource intense process with many stages. A multi-energy data hub (centralised computing architecture as shown in the right of Figure 3) can provide improve data management and exchange processes between the different parties connected to the energy systems and markets, providing greater and more consistent data quality and transparency, and enhancing interoperability. The work carried out and the results obtained on this topic are described in Chapter 7.

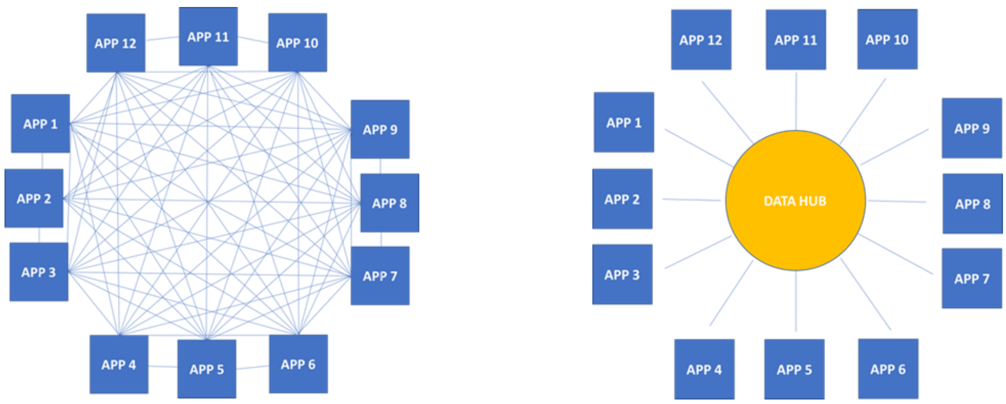


Figure 3 – Point-to-point architecture vs data bub architecture [3]

The basic principles of the interactions between the MES and the aggregation platform are shown in Figure 4 and summarized below.

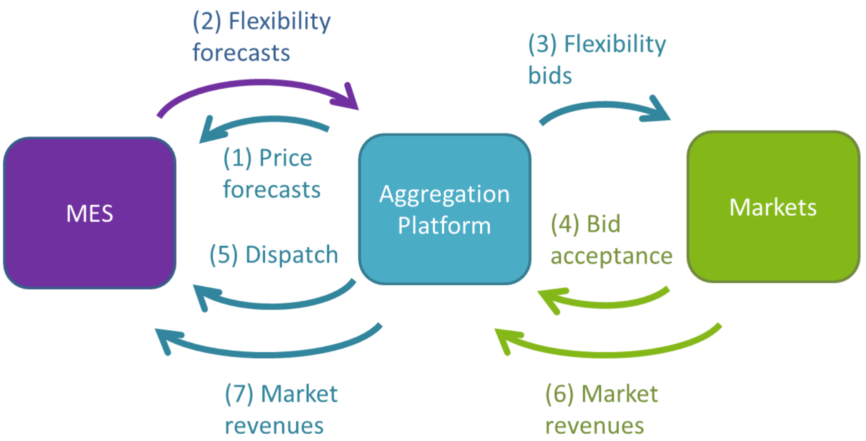


Figure 4 – Basic principles of the interactions between the MES and the aggregation platform

(1) The aggregation platform sends the MES the price forecasts for a certain period for the relevant markets considered for trading its flexibility.
(2) Using these market price forecasts, the MES carries out its optimization and sends the aggregation platform its flexibility forecasts and the associated costs or prices.
(3) The aggregation platform carries out its optimization aggregating the flexibility of the MES and the other resources in its portfolio (also called the aggregation pool) and sends flexibility bids to the markets selected.
(4) The market operators communicate the auction results and the accepted bids to the aggregation platform.
(5) The aggregation platform dispatches the relevant resources in its portfolio, including the MES, to provide the flexibility services, according to the accepted bids.
(6) The aggregation platform receives market revenues.
(7) The aggregation platform communicates to the MES its share of the market revenues.

In the case of frequency reserve services (aFRR, mFRR), other steps may occur between Steps 5 and 6. Indeed, if needed for the compensation of imbalances, the TSO may send a signal to the aggregation platform to activate the delivery of the reserve services previously procured. The aggregation platform then dispatches the resources in its pool and accordingly sends an activation signal to the MES.

Finally, the overall MAGNITUDE approach can be summarized by the following activities that were carried out and generated the project main results:

- Identify the most relevant flexibility services to be provided by Multi-Energy Systems (MES) to the electricity system, which allow to increase the share of RES and enhance security of supply, and characterize the procurement mechanisms for these services in the 7 case study countries.
- Investigate the technologies and MES involved the seven real-life case studies considered in the project and study their actual capabilities to provide flexibility to the electricity system.
- Elaborate the MAGNITUDE technical and commercial functional architectures and define the project business use cases investigated in the project.
- Develop models and tools for the simulation and optimization of the control strategies of the technologies and MES in the 7 case studies to improve their operation and maximize the flexibility provision.
- Develop an aggregation platform to quantify the benefits of pooling flexibilities of decentralized MES for trading on the identified energy and ancillary service markets.
- Propose and compare innovative market designs for the enhancement of the synergies at the level of the electricity, gas, and heat markets, and implement them on a market simulation platform.
- Assess the integrated system (namely MES optimisation, pooling through the aggregation platform, and market simulation) for the selected business use cases in the 7 case studies.
- Investigate the replicability and transferability of MAGNITUDE's business cases.
- Evaluate the business models for the MES operator and for the aggregator in the 7 case studies.
- Develop the specifications and a light implementation of a multi-energy data hub and interoperability layer.
- Capitalize the project main findings and lessons learnt and propose policy strategy and recommendations in a pan-European perspective – including technology, market, business models, and regulation aspects.

For each of the activities of the MAGNITUDE approach, Table 1 below shows the deliverables that were produced and that contain the project results. More information will be provided in the different chapters of the current report. An overview of these deliverables can also be found on the MAGNITUDE website [4], along with the full version of the public deliverables.

Table 1 – Deliverables produced for each activity of the MAGNITUDE approach

Activities of the MAGNITUDE approach	Deliverables
Flexibility services to be provided by MES to the electricity system and procurement mechanisms	D3.1
Flexibility capabilities of cross-sector technologies and MESs	D1.1, D1.2, D1.3
MAGNITUDE technical and commercial functional architectures and project business use cases	D2.1
Models and tools for the simulation and optimization of control strategies of technologies and MES to optimize their operation and maximize flexibility provision	D4.1, D4.2, D4.3
Aggregation platform for the pooling and trading of the flexibilities of decentralized MESs	D5.1, D5.2, D5.3, D5.4

Activities of the MAGNITUDE approach	Deliverables
Innovative market designs for synergies maximization at market level, and implementation on a market simulation platform	D3.2, D3.3, D3.4
Assessment of integrated system (MES optimisation, pooling through the aggregation platform, and market simulation)	D6.1, D6.2
Replicability and transferability of MAGNITUDE's business cases	D1.4
Business models assessment for MES operator and aggregator	D3.5
Multi-energy data hub and interoperability layer	D2.2, D2.3
Lessons learnt, policy strategy and recommendations in a pan-European perspective	D7.3, D7.4

1.3 Structure of Deliverable D7.3

The structure of the deliverable reflects the project approach to a large extent and covers the following aspects in the different chapters:

- In Chapter 2, the seven MAGNITUDE real-life case studies are first described, along with the business use cases that have been studied. Then, the ability of the technologies involved in the case studies to provide flexibility is discussed. The following section is devoted to the description of the models developed for the simulation and optimisation of the different MES. Finally, an overview of the main outcomes and lessons learnt from the simulation of the seven case studies is given, and some recommendations are provided.
- Chapter 3 first describes the software tools and processes developed for the multi-energy aggregation platform and the trading of MES flexibility on the markets. Then the main outcomes and lessons learnt from their assessment and from the simulations carried out on the case studies (where aggregation is performed) are reported, and finally, some recommendations are provided.
- Chapter 4 is devoted to market and regulatory perspectives. It first presents the services to the electricity system that have been identified as most relevant to achieve the project goals. Some basic characteristics of the electricity, gas and heating/cooling sectors are then given, and an overview of the main outcomes and lessons learnt on the existing market designs, regulation and services procurement mechanisms in the seven case study countries is provided, along with recommendations for potential evolutions and improvements. Finally, the last section describes the innovative integrated multi-carrier day-ahead (DA) market designs that have been proposed to increase synergies between the electricity, gas, and heat markets.
- Chapter 5 provides an overview of the main outcomes, lessons learnt and recommendations from the assessment of the replicability and transferability of the multi-energy systems (MES) of the case studies and their business use cases to the countries of the MAGNITUDE consortium.
- Chapter 6 is devoted to the business models of the MES and the aggregator that were assessed for the 7 case studies. It provides an overview of the main results and lessons learnt from the business model assessment, some specific results for each case study, as well as the main recommendations
- Chapter 7 first describes the outcomes and lessons learnt from the work carried out on the characterisation of the main stakeholders involved in the electricity, gas, and heating/cooling

sectors, in terms of their roles and their main interactions. Then, the second part of the chapter provides an overview of the specification and implementation of the MAGNITUDE multi-energy data hub and interoperability layer.

Finally based on the main outcomes and lessons learnt from the project, Chapter 8 is devoted to the description of the remaining challenges and the recommendations for future research and development work, as well as recommendations for future demonstration projects.

2 Provision of flexibility by multi-energy systems

In this chapter, the seven MAGNITUDE real-life case studies are first described, along with the business use cases that have been studied. Then the ability of the technologies involved in the case studies to provide flexibility is discussed. The following section is devoted to the description of the models developed for the simulation and optimisation of the different MES. Finally, an overview of the main outcomes and lessons learnt from the simulation of the seven case studies is given, and some recommendations are provided.

2.1 The MAGNITUDE real-life case studies

As previously mentioned, the project concepts, the tools and models developed, and the proposed market and business mechanisms were assessed and validated on seven real-life case studies of multi-energy systems of different sizes and technological features, located in seven European countries (Austria, Denmark, France, Great Britain, Italy, Spain, and Sweden). They allowed to cover different regulatory frameworks, support schemes, geopolitical characteristics, as well as different stakeholders and business models. The considered case studies are:

- the Milan district heating system of A2A Calore e Servizi (ACS) in Italy,
- the wastewater treatment plant of EMUASA in Spain,
- the district heating and cooling systems of Mälarenergi in Sweden,
- an integrated pulp and paper mill in Austria,
- the HOFOR case study in Denmark consisting of distributed units for domestic hot water preparation (heat pumps and thermal storages for multi-storey buildings, and electric heat boosters and thermal storages for single-family houses) at consumers' premisses connected to a low temperature district heating network,
- the Neath Port Talbot Borough Council area in the United Kingdom (UK), focusing on a Combined Cycle Gas Turbine (CCGT), steelworks (Tata Steel) and large renewable energy plants,
- the district heating and cooling systems and the decentralized substations of the Paris Saclay site in France.

They provided the data foundation for the assessment work and for the modelling and development activities that took place in the different Work Packages of the project. They are described in detail in MAGNITUDE Deliverables D1.1 [5] and D1.2 [6]. Their main characteristics are summarized below.

The 7 case studies cover three main categories of MES and/or combinations of such MES, namely industrial sites (EMUASA, Austrian paper mill, NPT), large district heating/cooling systems (ACS, Mälarenergi, Paris Saclay), and distributed units at consumers' premises (HOFOR) or in decentralized substations (Paris Saclay). The main technologies and the energy carriers involved in each case study are shown in Table 2. In this table, blue cells indicated when the corresponding technology or energy carrier is included in the case study. Due to the size of the considered MES and the voltage frontiers between transmission and distribution electricity networks in the case study countries, only the MES of the NPT case study are connected to the transmission network and all the other MES are connected to the distribution networks.

For each of the case studies, two types of configurations were investigated, namely the existing configuration and configurations implementing technological options and/or operation strategies to improve the provision of flexibility to the electricity system. Different possible improvement options and strategies were discussed with the case study owners and/or the MAGNITUDE partners in charge of the interface with the case studies [5], [6]. The ones selected for investigation are shown in Table 3 [7]. They appeared as the most relevant both for the project goals and from the technical feasibility of investigation in the project (e.g. availability of data).

As will be seen later in this chapter, the main flexibility levers that can be activated depending on the case study are the following:

- fuel shifting between energy carriers through the operation of the technologies in the case study,
- storage capability,
- load shifting or demand response.

Table 2 – MAGNITUDE case studies: technologies and energy carriers

	Case study	Mälarenergi	Paper mill	HOFOR	ACS	NPT	EMUASA	Paris Saclay
Technologies	Biomass or waste boiler	■	■					
	Gas boiler		■		■	■	■	■
	Steam turbine	■	■			■		
	Gas turbine					■		
	Gas engine				■		■	
	Heat pump			■	■			■
	Electric boiler	■		■	■			
	Biogas storage						■	
	Thermal storage	■		■	■			
Energy carriers	Heat	■	■	■	■	■	■	■
	Cooling							■
	Gas		■		■	■	Biogas*	■
	Electricity	■	■	■	■	■	■	■

Blue cells indicate that the technology or energy carrier is included in the case study.

* In the case of EMUASA, the gas carrier is not natural gas, but biogas produced on site by the process.

Table 3 – MAGNITUDE case studies: improvement strategies and services considered for provision [7]

Name (Country)	MES main activity	Improvement strategies	Provision of services in current procurement mechanisms
Mälarenergi (Sweden)	District heating network	Introduction of a second heat storage system.	DA, ID, mFRR, strategic reserves (Cap).
Paper mill (Austria)	Integrated pulp and paper mill	Installation of a new steam accumulator.	DA, ID, aFRR, mFRR.
HOFOR (Denmark)	Distributed units at consumers' and low temperature district heating network	Appropriate control and communication interfaces to allow aggregation of distributed units and provide services through heat load shifting.	DA, ID, congestion management on the distribution network (ReD).
ACS (Italy)	Milan district heating network	Increase of thermal storage capacity by 50%. Winter heat demand peak shaving.	DA, FCR, aFRR, mFRR.
Neath Port Talbot (UK)	Steel industry, CCGT and large RES	Improved coordination between electricity and gas markets.	DA, congestion management on the transmission network (ReD), capacity market (Cap).
EMUASA (Spain)	Wastewater treatment plant	Doubling gas storage capacity. Introduction of a heat storage system.	DA, ID, mFRR.
Paris Saclay (France)	District heating and cooling networks, and distributed units in substations	Introduction of thermal (heat and cooling) storage in decentralized substations. Integration of photo-voltaic (PV) resources.	DA, ID.

Table 3 also gives in the last column the services that were investigated for each case study. Their provision was considered in the current procurement mechanisms in place in the case study country. These services have been introduced in the previous chapter (see Section 1.2) and are described in more detail in Chapter 4, Section 4.1. They consist of:

- energy procurement mechanisms and markets: day ahead energy market (DA), intraday energy market (ID),
- provision of reserves for TSOs: Frequency Containment Reserve (FCR), automatic Frequency Restoration Reserve (aFRR), manual Frequency Restoration Reserve (mFRR),
- re-dispatching mechanisms or active power control for congestion management at transmission or distribution levels (ReD),
- capacity requirement mechanisms (Cap), such as capacity markets and strategic reserves.

Like for the improvement strategies, for each case study, the services were selected through workshops and discussions organised with the case study owner and the project partner ensuring the interface with the case study. It should be noted that **for all case studies, the optimisation of the MES operation with respect to its participation in the DA energy market was first carried out**. Then the provision of the other services without and with the implementation of the improvement strategies was investigated, leading to several scenarios that were simulated and assessed for each case study, namely 4 scenarios for Mälarenergi, 4 scenarios for the Austrian paper mill, 6 scenarios for HOFOR, 8 scenarios for ACS, 4 scenarios for NPT, 8 scenarios for EMUASA, 8 scenarios for Paris Saclay [7], [8].

Table 3 thus summarizes the business use cases studied in the project for the case studies.

2.2 Capabilities of technologies

The ability of the technologies involved in the case studies to provide flexibility was first investigated based on a literature review and the collection of data and information from available studies, manufacturer data, current and finished projects, technology and case studies factsheets, and background of the consortium partners. The results of this analysis are provided in Deliverable D1.1 [5] and D1.2 [6].

Depending on the technology, the provision of flexibility to the electricity system can be performed by modifying the electricity produced, converting electricity into other energy carriers (e.g. heat, gas), increasing, decreasing or shifting the electricity consumption.

The products traded on the markets, and particularly on the frequency ancillary service markets, have to meet certain requirements, for instance in terms of maximum full activation time, minimum duration of the product delivery, symmetry of product[1] on some markets (e.g. for aFRR and FCR), minimum bid volume, etc. The capabilities of the technologies to meet these requirements have thus to be characterized and assessed.

In this respect, three parameters are particularly important and have to be known and monitored:

- **Ramp-rate** expressed in units of power over time, which indicates how quickly an output is changing, either ramping up, or ramping down.
- **Start-up time** expressed in units of time, which is the time needed by a power plant to reach full load. Two procedures have to be distinguished: (i) cold start when the power plant is shut down for many hours or days and (ii) warm start when the temperature of the power plant is maintained to a certain level.
- **Power range** expressed in units of power. Technologies vary greatly in capacity; so, aggregation of several smaller units through the implementation of an appropriate ICT infrastructure allows to reach higher capacities.

Table 4 provides these basic technical characteristics for the technologies considered. Technologies with short ramp-up and start-up times, and high-power capacities such as electric boilers, gas engines and aero-derivative turbines meet requirements for frequency containment reserve (FCR) markets. Gas turbines and aggregated heat pumps/chillers and ORC systems are suited for the participation in the "short-term" energy balancing markets (aFRR, mFRR). As such, technologies with less flexible capabilities such as condensing turbines and steam turbines cannot provide the full range of flexibility services. They are more relevant for intraday and day ahead energy markets. However, heat and gas storages can increase the flexibility provision of the above-mentioned technologies or system configurations to which they are coupled or in which they are integrated.

[1] For "symmetric" products, the capacity committed for downward and upward services must be the same, whereas it may be different for "asymmetric" products.

Table 4 – Basic technical characteristics of the considered technologies [6]

Technology	Power output/input	Hot start up time	Cold start up time	Ramp rate
	MWe	min	min	% of nom. power/min
Backpressure steam turbines- liquid fuel	1-250	120-360	240-420	1-8%
Backpressure steam turbines - solid fuel	1-250	120-360	240-420	1-4%
Condensing turbines- solid fuel	5-1 000	120-360	240-420	1-4%
ORC turbine	0.05-11	15	20-30	15-30%
Gas engine*	0.1-20	0.5-0.2	10-20	20-50%*
Gas turbine simple cycle	3-593	5-15	10-45	8-16%
Gas turbine combined cycle	44-593	30-45	145-255	6%
Gas turbine simple cycle aeroderivative	36-117	5	10-12	82-132%
Heat pump**	0.0005-7.5	3	300	20%
Electric boiler	0.005-60	0.5	5	100%
Compression chillers***	0.0002-3.2	3	60	6%
Absorption chillers****	0.015-14	n.a.	30	n.a.

*- running gas engine may have ramp rate of 100%/min; **- power consumption calculated for COP=4; ***- power consumption calculated for COP=6.5, hot start up time as for heat pumps; ****- only thermal power is shown

Flexibility requirements can also be expressed as the time within which the minimum power volume (in MW) has to be provided to the electric grid. As indicated in Figure 5, the gas-to-power and heat-to power technologies are important for frequency control and balancing because of their reactivity and the volume that they are able to provide. In particular, electric boilers (e-boilers), which have the shortest hot-start up time and ramp rate per minute at 100% of nominal power, can play an important role in the market of balancing services. E-boilers and other power-to-heat/cold technologies are thus relevant for the "short-term" services.

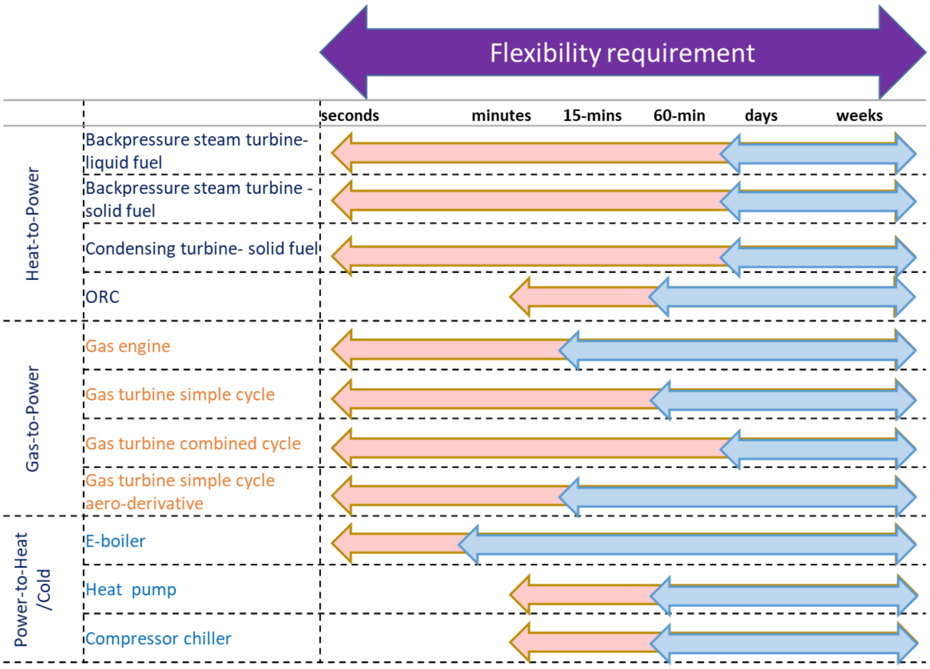


Figure 5 – Flexibility options provided by different technologies, orange arrows show capability for running technologies and blue arrows reflect capability including time needed for start-up from hot state

Figure 5 shows that for most technologies, as long as the generating/consuming unit is on (orange arrows), it can meet flexibility requirements in seconds, but this perspective is very different when the unit is off (blue arrows). Certain technologies such as steam turbines and CCGTs require up to several hours for cold start up, while others, such as gas engines, e-boilers, and aero-derivative turbines, are much quicker and can be switched on in less than 15 minutes. To shorten the time needed to connect to the electric grid, units can be held as a hot reserve, meaning that they are constantly heated; nevertheless, their ability to provide certain products to the electricity market is still limited as presented in Figure 6. In fact, not all technologies kept in a "hot reserve" can react within a required timeframe: steam turbines and CCGT units can deliver flexibility to the grid in a time ranging from 60 to 120 min, aero-derivative turbines and electric boilers have the highest potential among the analysed technologies, followed by gas engines. Large simple-cycle turbines, despite a quite low ramp rate, may still play an important role in the market, thanks to their sizes. Technologies as ORC turbines and heat-pumps may need to be aggregated in order to meet the requirement for a minimum volume.

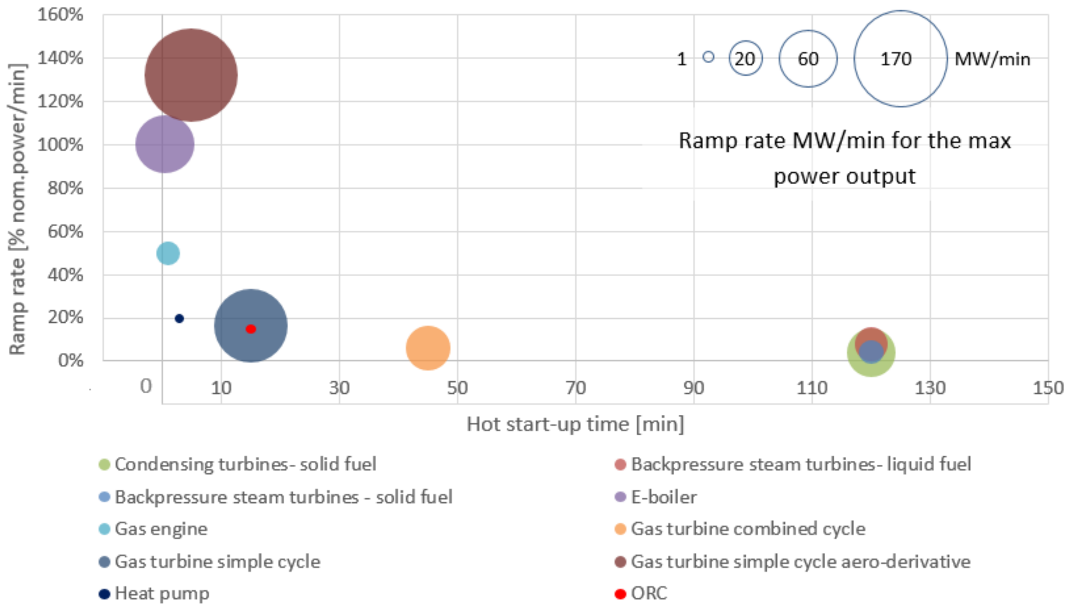


Figure 6 – Ramp rates [% nominal.power/min] and [MW/min] for the biggest power output as functions of hot start-up time

Figure 7 shows the impact of the unit size on its ramp rate expressed in MW/min. It can be seen that some technologies cannot provide the FCR service in some countries because of the very short full activation time (10-180 s) and the specific volume of megawatts (0.1-3 MWe) requested. Therefore, aggregation may be required.

Investment costs have also been analysed for the studied technologies. The specific investment costs in EUR/kWe (minimum and maximum values) are presented Figure 8, and these costs divided by their ramp rate speed [% of nominal power/min] are showed in Figure 9. It appears that the investment cost of reactivity expressed in [€/kWe] / [% of nominal power/min] varies between 0.3 for e-boilers up to 375 for solid fuel steam turbines. These values indicate that, among the examined technologies, only a few of them - such as e-boilers, gas aero-derivative turbines and gas engines - can provide flexibility to a market with a low investment cost and can be installed only for this purpose. For the other technologies, the cost of providing ancillary services to the grid may probably be too high, so the flexibility provision can be targeted only as a by-product and a decision about the investment should not be based only on this purpose.

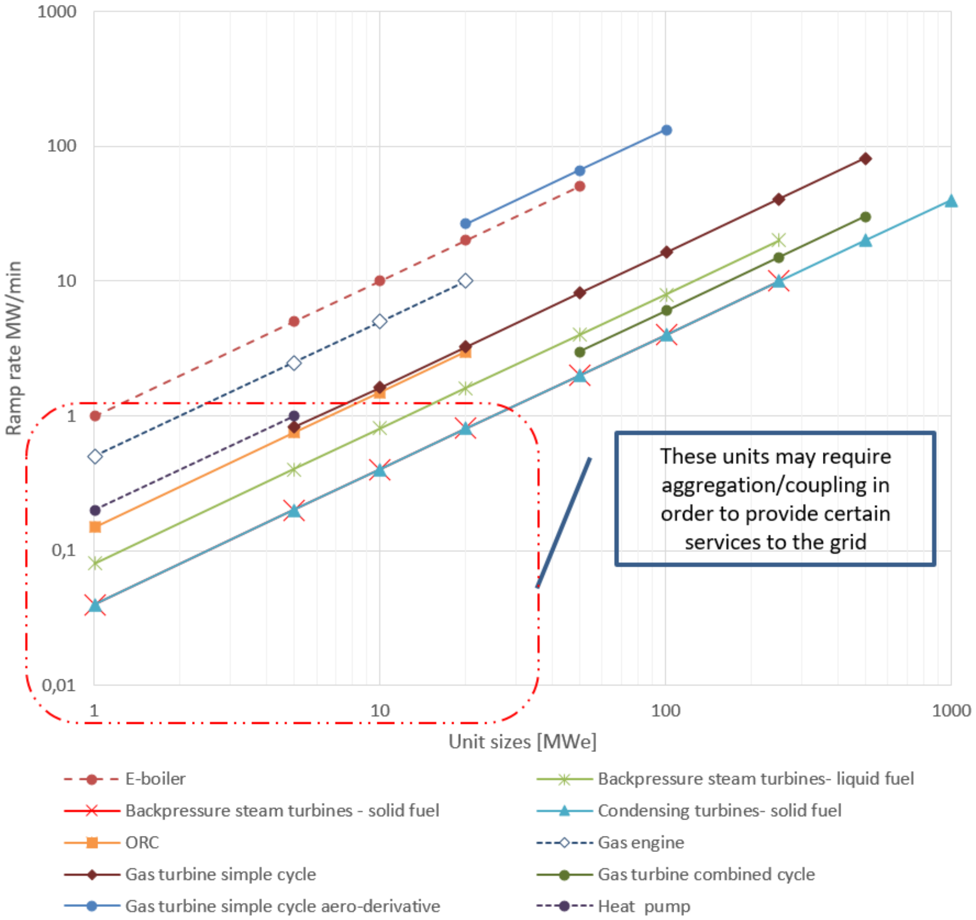


Figure 7 – Power range of analysed technologies and their ramp rates [MW/min]

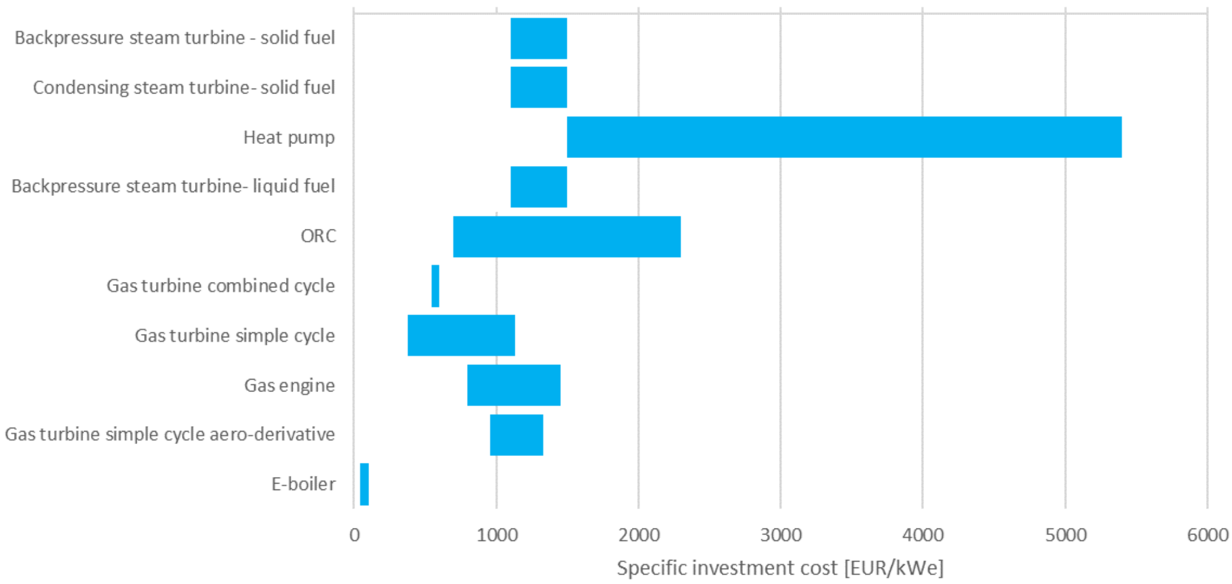


Figure 8 – Specific investment cost for the studied technologies. Cost for heat pumps was converted from kWth into kWe (of consumed electricity) by dividing the heat production by a COP of 3

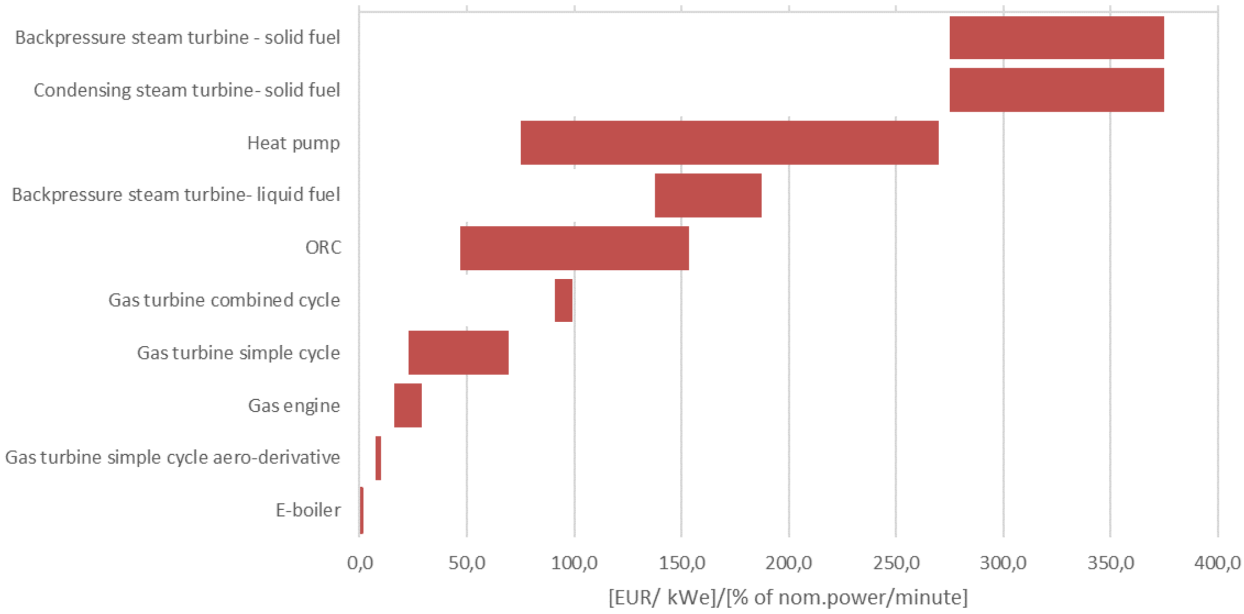


Figure 9 – Specific cost of investment divided by ramp rates for different technologies

Besides the investment costs, operational costs are as well of key importance and are influenced by efficiency, fuel price, environmental costs, maintenance, electricity costs, etc. Hybridization, e.g. coupling gas engines with e-boilers, may not only increase the capability of the multi-energy system to provide flexibility to the electricity system, but also minimize the operational costs and/or increase the incomes. However, as discussed in Section 2.4, in some countries where the electricity prices are high, it may turn out that the scheduling of electric boilers can be too expensive.

From a technology coupling perspective, thermal storage is a very promising option: even though it does not directly provide flexibility to the electricity markets, it enables to deal with a surplus or insufficient heat production, which is important to maintain high overall efficiency. Heat storage is not only capable to shave heat peak loads, but, in combination with P2H technologies, also to shave electrical peaks.

It should be highlighted that the flexibility capability of technologies is highly determined by the characteristics of the overall MES system in which they are involved. In this respect, the integrated management of the different technologies at the level of the MES site may partially overcome the technical limitations. This will be discussed in more detail in Section 2.4. At a higher level, the aggregation of the MES within a portfolio with other flexible resources allows the provision of market products that the MES alone could not provide (see Section 3.2).

Other key factors have to be considered regarding flexibility provision, such as [9]:

- Lockout constraints, which refer to constraints requiring that a unit cannot be started again within a certain time period after it is shut down, due to mechanical requirements or for protecting the device.
- High starting currents of certain technologies.
- Minimum load levels of each piece of equipment (e.g. CHP, CCGT) and of the overall technology coupling.
- Mechanical stress due to frequent switching.
- Possibly high maintenance cost due to fast and frequent start-ups / shut down and load changes.

- Fast and more frequent starts and stops, and load changes may affect the long-term operation efficiency of the technologies: they may induce more stress in critical components, leading to increased fatigue damage and a reduction of the lifetime of the equipment.
- Update of the control and communication systems might be required.
- Flexibility provision may be limited by the interconnections of the MES with the external networks. For instance, limited capacity of the interconnection equipment (e.g. transformers with insufficient capacity in the ACS case study) or of the other networks (e.g. the gas network) may impose limitations on the maximum amount of power that the MES can exchange on the electricity grid. In this case, network reinforcement or equipment upgrade is a potential solution.

Finally, it should be kept in mind that flexibility provision does interfere with the industrial process and the core business of the MES. In heat driven and industrial processes, there is a coupling between the electricity generation or consumption and the heat generation. The priority of the MES operation will be to satisfy the needs of this core production process e.g., supply heat or cooling to consumers for district heating and cooling networks, produce paper or steel, treat wastewater, etc.

2.3 Modelling and optimisation of MES

The MES in the seven case studies were modelled in detail with the main objectives of simulating their behaviour and investigating optimisation strategies with respect to the provision of flexibility services to the electricity system, in accordance with the selected business use cases described in Section 2.1 and summarized in Table 3.

The modelling activities consisted in two steps [10]:

- The MES in each case study was first modelled as per its physical and operational behaviours[2] integrating all the relevant technological components in order to reproduce as accurately as possible its dynamic behaviour [11]. The specifications of the models, for instance in terms of dimension or complexity, control and observable variables, time resolution, etc. took into account the services and scenarios that were going to be studied. The models were coded into suitable tools able to support both the simulation and the optimization phases, and they were tested against the real information and time-series data provided by the case study owners on their MES. For the data that were not available, otherwise specific time series were defined to identify possible scenery.
- The models were then extended to implement the new technological configurations and/or control strategies corresponding to the selected improvement options and business use cases [7]. The challenge in this second phase was the development for each of the seven project case studies of appropriate optimisation algorithms and methods. The algorithms and methods were designed to simulate and assess the MES both in the base-case configuration and improved configurations for the defined scenarios and boundary conditions, integrating the provision of the market services associated to each case study, and maximizing identified key performance indicators (KPIs). The outcomes from the developed tools were also configured in order to interact with the multi-energy

[2] Physical models are mainly related to representing the system behaviour integrating its technological components, while operational models refer to the management of the system related to a specific business model which requires an optimization step, like for instance the elaboration of a (optimal) planning.

aggregation platform in order to simulate the participation of MESs to the trading of flexibility on the markets. Requirements of the aggregation platform were then also taken into account.

The modelling of MES was carried out based on dynamic models, ranging from physical representation of the MES behaviours (e.g. for the Austrian Paper Mill), grey box models where the dynamic regarding starting/stopping/changing set-point phases are modelled, and data driven models based on the black box paradigm. The output of the process consisted of (set of) tools, which run on software platforms satisfying the requirements. In particular, these tools are able to replicate one or more use cases, interfacing with the aggregation platform in order to simulate the provision of services both in the operational planning and operation phases, as needed.

Figure 10 below shows in more detail different methodological steps used in the modelling activities [10].

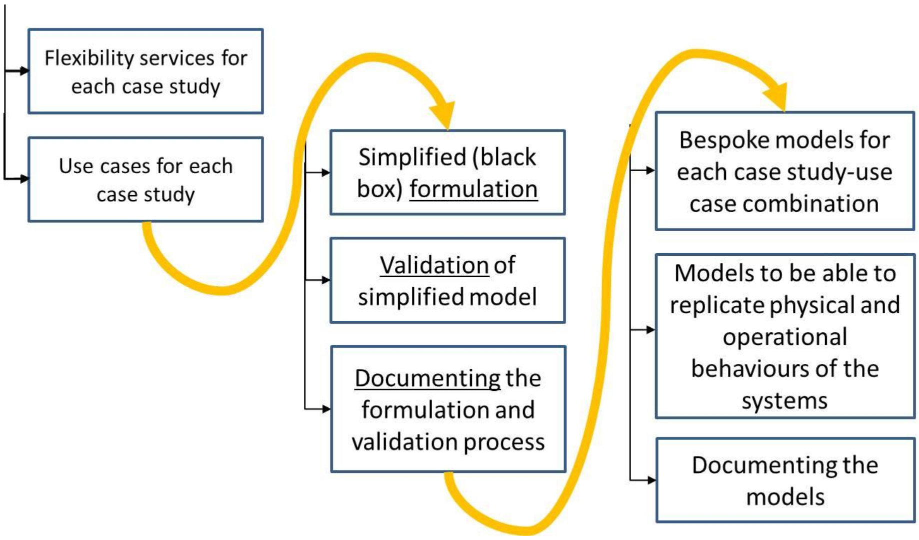


Figure 10 – Methodological steps in MES model development [10]

Some lessons learnt from the modelling activities can be summarized as follows:

- Regarding the type of models developed, dynamic models of MES are relatively easy to replicate, for instance once such a mathematical model exists for a MES, it can be relatively easy to adapt it to minor system modifications. Parameterized models can be adopted in order to instantiate as many times as needed the same model to represent different units.
- Data driven models does not required a full understanding of the fundamental MES processes and of the underlying system behaviours of MES technologies. Therefore, they are easier to develop but, since they are trained and validated with data, they fully rely on the quality and availability of the data. Extrapolation and accurate predictions outside of the training data regime need a careful validation with testing data different from those used for training.
- Validated models of MES technologies and energy carrier networks already exists. The exploitation and proper adaptation of such existing models increase the efficiency and reliability of the use cases under development.
- The possibility to integrate different codes and tools to model several system components or different system tasks facilitates the modelling activity and can provide a more reliable result. The different models can be arranged in a hierarchy to differentiate the technologies and the different

level of abstraction. The availability of suitable libraries with a variety of models of both technologies and energy carrier networks is an important factor for the modelling and assessment of MES.

- MES optimization implies highly complex processes that involve several energy carriers converted by generators, consumers, and storages devices. The ability of a model to support the representation and characterisation of the flexibility at each level (technology and system levels) or operating step (planning, operational planning and real-time operation) allows to highlight the potentials and barriers that influence the total amount of flexibility that the system can provide. The potentials and barriers at the technological level are related to the physical and operational models, and whereas potentials and barriers at the regulation and market level, are related to the operational model.
- For flexibility assessment, the model temporal resolution is a key point and has to correspond to the temporal resolution of the studied services, namely seconds for FCR, minutes for aFRR or 10 min for mFRR. These short data intervals require high simulation workload and much data storage volume.
- The main bottleneck in modelling is the lack of experimental data. Measured data on actual MES plant enable the elaboration of more reliable models and support the model validation. Hence, real data are a precious resource, but at the same time they can be very sensitive (for instance for competitive advantage), are not easily shared. Data availability especially from industrial processes is one of the main hurdles for modelling and simulation of MES technologies.

Further research and development are needed regarding models for MES technologies as well as for MES systems combining several different technological assets, with the objectives to accurately represent their behaviours and the flexibility they can provide, and to investigate alternative optimisation strategies, integrating in particular all the cost as environmental components. With the current trend on the markets to have shorter products closer to real time, the future the time horizon/resolution will have also to be shortened.

2.4 Assessment of MES in the case studies

The aim of the assessment was not only to characterise the performance of the flexibility provision in the seven real-life case studies but also to determine the effect of the flexibility provision and of the improvement strategies on a case study itself.

This assessment was carried out through a set of Key Performance Indicators (KPIs) described in Deliverable D6.1 [12]. More specifically, 37 KPIs were defined covering four different types of KPIs, namely technical, economic, environmental and social/policy KPIs and addressing the project targets and expected benefits, expressed as follows:

- Increased flexibility potential from MES operation in a synergetic MES environment.
- Increased sustainability, security of supply and quality of service in electricity supply and grid operation.
- Increase of generation and/or utilization of renewable energy.
- Provision of cost-effective MES flexibility in the electrical power system.
- Creation of market mechanisms and business opportunities to mobilize flexibility and participation in in the market (directly or through aggregators).

The KPIs were further categorized in different layers to reflect the assessment across the different system levels, i.e. MES internal KPIs related to technologies and technology coupling, MES output KPIs related to configurations and control strategies, MES aggregation KPIs related to the aggregation of MES flexibility, Services and Markets KPIs related to the service provision on the markets, and then General Project Level KPIs. They are further explained in Figure 11.

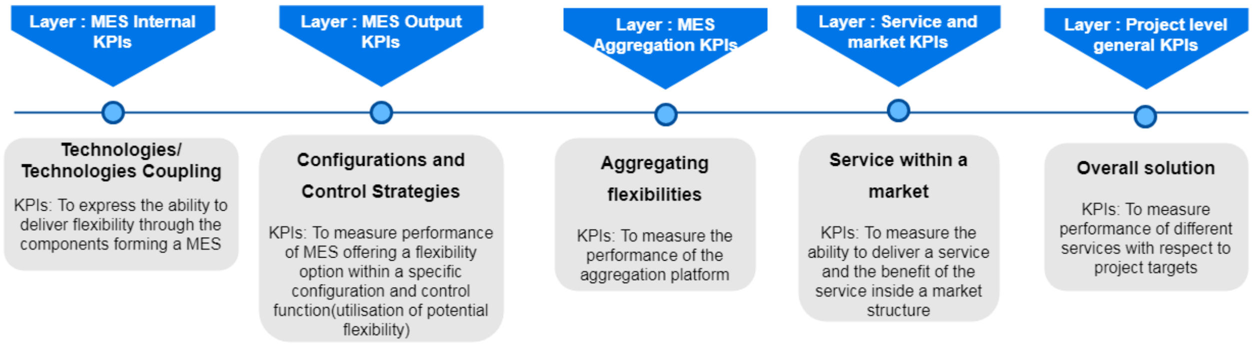


Figure 11 – KPI layers corresponding to system levels [12]

For the needs of the assessment, some KPIs had to be adapted later and some new ones were introduced when required. The whole set of KPIs allowed to assess the performance of the base case and improved configurations of the studied MES in terms of flexibility provision, energy efficiency, environmental efficiency, and economic efficiency. However, since each case study (CS) has its own specificities (e.g. in terms of the type of energy consumed and/or generated, the flexibility markets considered, types of technologies), different subsets of the KPIs had to be used for the evaluation of the seven CSs.

As mentioned in Section 2.1, for each of the 7 CSs, between 4 and 8 scenarios were simulated and compared. First, a base case was considered, where the operation of the MES is optimized against day-ahead energy market prices. Then one or several improvement strategies were implemented for each MES (see Table 3), providing new scenarios that could be compared to the base case. Finally, the provision of flexibility services was simulated both for the base case scenario and the scenario(s) with the improvement strategy (strategies). As a result, the analysis allowed to investigate the impact of the introduction of an improvement strategy on the flexibility potential and flexibility actually provided, on the energy efficiency, and on the environmental and economic efficiency of the MESs. The impact of the actual provision of flexibility in the markets on the operation and the performances of the MES could then be assessed. The scenarios simulated for each case study are presented in Table 5 below.

Table 5 – Simulated scenarios for each case study

Case study	Scenario	Improvement strategies considered	Flexibility services provided
Mälarenergi (Sweden)	SC1	No improvement strategy	No flexibility service
	SC2		ID + mFRR
	SC3	Installation of a second heat storage	No flexibility service
	SC4		ID + mFRR
Paper mill (Austria)	SC1	No improvement strategy	No flexibility service
	SC2		ID + aFRR + mFRR
	SC3	Installation of a steam accumulator	No flexibility service
	SC4		ID + aFRR + mFRR

Case study	Scenario	Improvement strategies considered	Flexibility services provided
HOFOR (Denmark)	SC1	No improvement strategy - Domestic hot water (DHW) production for multi-storey buildings	No flexibility service
	SC2a	Implementation of external control of heat pumps and heat storages for DHW production for multi-storey buildings	ID
	SC2c	Implementation of external control of heat pumps and heat storages for DHW production for multi-storey buildings	ID + ReD
	SC3	No improvement strategy - DHW preparation for single-family houses	No flexibility service
	SC4a	Implementation of external control of electric heat boosters and heat storages for DHW preparation for single-family houses	ID
	SC4c	Implementation of external control of electric heat boosters and heat storages for DHW preparation for single-family houses	ID + ReD
ACS (Italy)	SC1	No improvement strategy	No flexibility service
	SC5		FCR + aFRR + mFRR
	SC2	Increase of the heat storage capacity	No flexibility service
	SC6		FCR + aFRR + mFRR
	SC3	Introduction of heat demand peak-shaving in the winter season	No flexibility service
	SC7		FCR + aFRR + mFRR
	SC4	Increase of the heat storage capacity and heat demand peak-shaving in the winter season	No flexibility service
	SC8		FCR + aFRR + mFRR
Neath Port Talbot (UK)	SC1	No improvement strategy	No flexibility service
	SC2		ReD + Cap
	SC3	Change of the gate closure times for more coordinated gas and electricity markets	No flexibility service
	SC4		ReD + Cap
EMUASA (Spain)	SC1	No improvement strategy	No flexibility service
	SC5		mFRR
	SC2	Doubling the gas storage capacity	No flexibility service
	SC6		mFRR
	SC3	Installation of a heat storage	No flexibility service
	SC7		mFRR
	SC4	Installation of a heat storage and doubling the gas storage capacity	No flexibility service
	SC8		mFRR
Paris Saclay (France)	SC1	No improvement strategy	No flexibility service
	SC5		ID
	SC2	Installation of heat and cooling storages	No flexibility service
	SC6		ID
	SC3	Installation of PV electricity production	No flexibility service
	SC7		ID
	SC4	Installation of heat and cooling storages and PV electricity production	No flexibility service
	SC8		ID

For each of the CSs, the simulations were conducted on a representative set of weeks in order to simplify the simulation process. For this purpose, 6 weeks of the same year were selected (4 weeks for NPT): four weeks representing the four seasons and 2 other weeks (except for NPT) representing extreme operation weeks for the MES. The choice of the simulation weeks was made based on operational data when available from the CS owner, market price data (to avoid unusual price events that may impact simulation results) or outdoor temperatures, e.g. for district heating and cooling networks. The considered year was chosen based on the availability of the relevant data, namely 2018 for EMUASA, HOFOR, Mälarenergi and Paris Saclay, and 2019 for ACS, NPT, and the Austrian paper mill.

Finally, for each CS, to carry out the optimisation of the MES in the different scenarios of Table 5, the models used the price forecasts of the markets considered for trading their MES flexibility (as explained in Figure 4). These forecasts were generated and provided by a software tool of the aggregation platform (described Section 3.1) based on the historical prices of the flexibility markets of the corresponding country in the reference year of the simulations. In addition, the price forecasts for the day-ahead markets of electricity and natural gas were also needed. They were converted into costs for the MES, including also national energy taxes, CO2 costs, grid charges, renewable contributions, etc. in order to correspond to the actual costs met by the MESs for the provision of services in their respective countries.

2.4.1 Main outcomes and lessons learnt

This section provides an overview of the main outcomes and lessons learnt from the simulation of the seven case studies [8]. The overall assessment of some most relevant KPIs will be given for all the case studies, and exemplary results of other specific points will be provided for a couple of case studies (ACS for the most part).

First, the results show that **MES can provide flexibility to electricity system to support the integration of RES and contribute to decarbonization of energy system**. Some of the MES in the case studies already participate in the markets, either through an aggregator or trader entity internal to the company or the holding [1] (e.g. Mälarenergi and ACS case studies) or through an external aggregator (e.g. the Austrian paper mill), which is often also the supplier of the MES.

Depending on the technologies involved in the MES, flexibility can be provided by the modification of the electricity generated on the grid and/or consumed from the grid. This can be achieved by:

- Fuel shifting, for instance, by consuming more gas and less electricity or the inverse (an example is given in Figure 12)
- Management of the energy demand: load shifting or demand response of the consumers, whenever possible.
- Using storage capabilities.

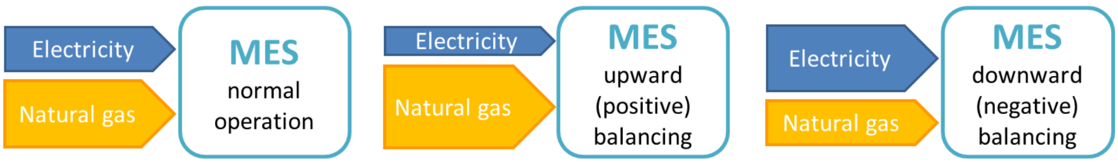


Figure 12 – Example of flexibility provision through fuel shifting

Two types of "flexibilities" have to be distinguished:

- Upward or positive flexibility means increasing electricity production/injection on the grid or reducing electricity consumption from the grid.

- Downward or negative flexibility means reducing electricity generation/injection on the grid or increasing electricity consumption from the grid.

This is illustrated on Figure 12 for a MES which is a net electricity consumer.

MES have potential to participate in the selected markets: day-ahead and intraday energy markets, frequency ancillary service procurement, congestion management in local markets, and capacity requirement mechanisms. But this strongly depends on the technologies in the MES site, the core process, and the operation strategies.

As an example, Figure 13 shows for ACS in the base case scenario (SC5 in Table 5) for the winter week, the available positive (“ELEC FLEX UP”) and negative (“ELEC FLEX DW”) flexibility and the bids that can be proposed for FCR, aFRR and mFRR markets. It clearly appears that the flexibility that can be proposed to the market is lower than the available flexibility.

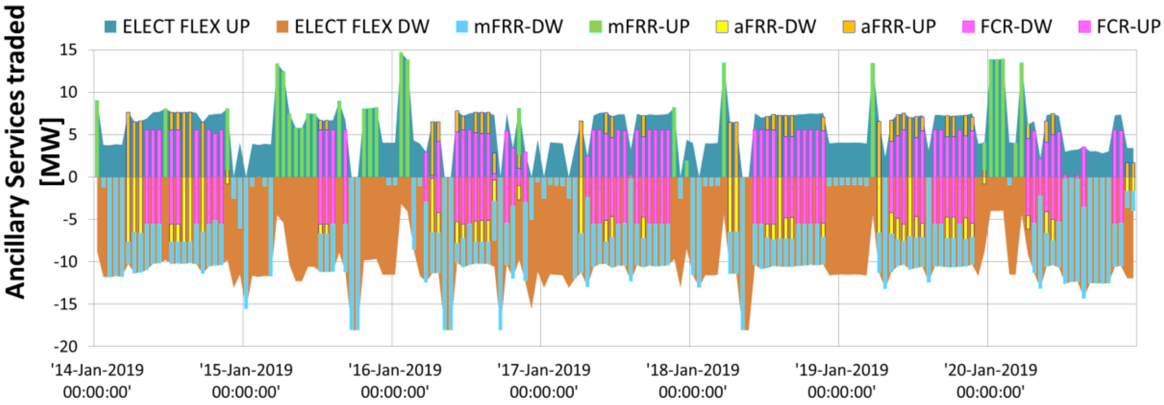


Figure 13 – Available flexibility and bids proposed for market services (ACS, scenario SC5, winter week)

Indeed, the simulations carried out for the seven real-life case studies showed that a **significant amount of flexibility can be available but only a small part of the available flexibility is actually activated (i.e. in terms of energy delivered)**. This is shown in Figure 14, which gives for each case study the average percentage of the available flexibility which is activated. These values were computed for the six simulated weeks of the reference year and taking into account both positive and negative flexibilities (in absolute value). The percentage ranges between less than 1% (for NPT) up to around 13% for HOFOR, with a value of 9% for ACS.

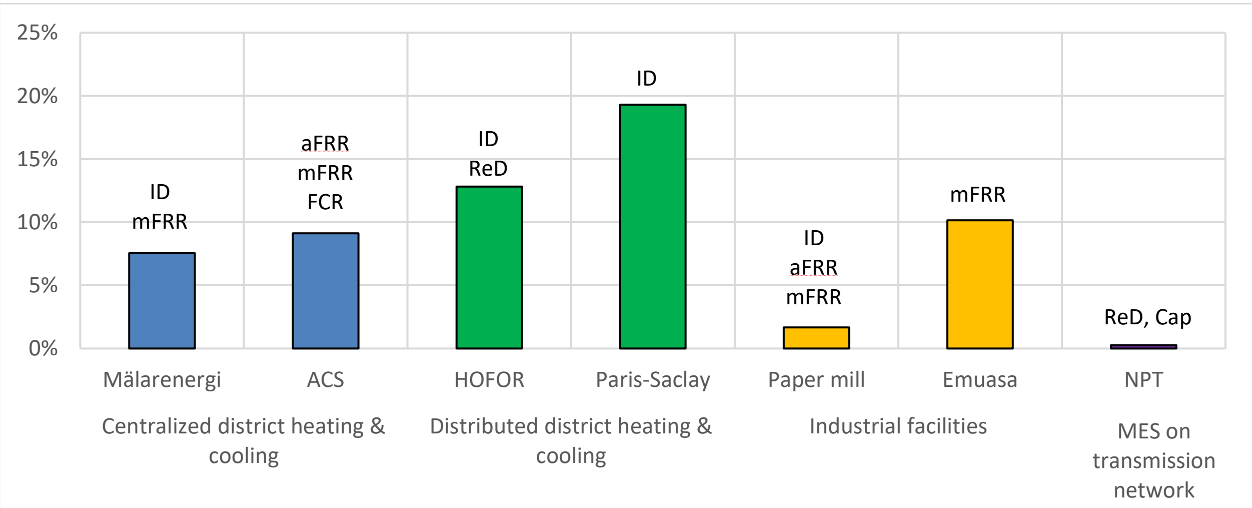


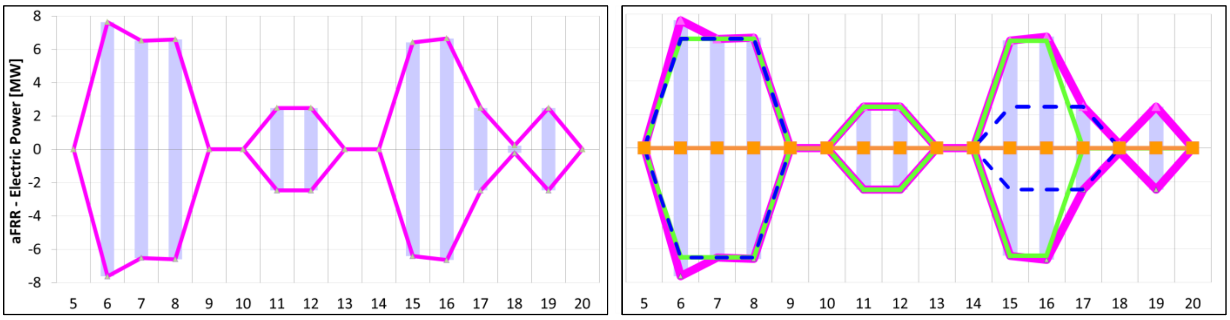
Figure 14 – Average activated flexibility in percentage of available flexibility

Some explanations are needed here to understand the meaning of "activated energy". In the case of day-ahead or intraday energy markets, all accepted bids must be delivered and so the corresponding energy is automatically "activated". For the reserve services like FCR, aFRR, mFRR, two different phases must be distinguished: (i) the procurement of the power reserves on the markets in order to guarantee the availability of the flexible resources when they will be needed, and (ii) the activation of the service and the actual energy delivery. This activation depends on the deviation of the grid frequency from 50 Hz, which follows a random distribution, so that the procured reserves might not be activated. This above distinction between procurement of reserve and activation may also apply to capacity requirement services, as well as to some procurement mechanisms of local power capacities to be used for congestion management.

As explained in Chapter 3, in all investigated markets for ancillary services, in 2019, the activated energy was less than 20% of the maximum possible energy provision, i.e. the product of reserved capacity multiplied by the bid duration. So, this low activation probability is certainly one important reason explaining the difference between the available flexibility and the energy actually delivered.

But there are other reasons. Some of them have already been mentioned in Section 2.2, such as:

- **The technical requirements of the products traded in the markets**, in particular frequency regulation markets FCR, aFRR, mFRR (e.g., maximum full activation time, the minimum duration of service delivery, symmetric product), affect the amount of flexibility that can be provided. An example is given below for the minimum duration of the service delivery. This requirement means that the service provider must be able to maintain the same contribution for the whole time interval specified for the considered product. To be compliant with this, the provider generally offers the minimum amount of available flexibility that can be guaranteed during this period. As a result, in most cases, the longer is the duration required by the market product, the lower will be the available flexibility offered by the provider. Figure 15 illustrates this issue for ACS and the aFRR market. The schedule obtained for the winter season is reported in Figure 15(a). In this case, the minimum duration of the aFRR product is assumed to be equal to one hour. Three different hypotheses are then chosen to assess the impact of higher minimum product durations. The outcomes are shown in Figure 15(b) for durations of two hours (green lines), three hours (blue dashed lines) and four hours (orange line). The amounts of flexibility that can be offered in these three hypotheses compared with the one-hour duration are the following: 85% for aFRR with two-hour duration, 61% for aFRR with three-hour duration and 0% for aFRR with four-hour duration (meaning that no flexibility can be proposed in this latter case).



(a) aFRR (pink lines) as originally scheduled for the winter season

(b) aFRR with different hypothesis on service duration: 2-hours (green lines), 3-hours (blue dashed line) and 4-hours (orange line)

Figure 15 – Example of the impact of product minimum duration for aFRR (ACS, winter season)

As already mentioned, these technical limitations can be overcome to a certain extent by an integrated management of the different MES technologies at the level of the site (with an EMS), and at a higher level, by the aggregation of the MES with other flexible resources in an aggregation pool. This topic of the limitations brought by the technical requirements of market products will be further discussed in Chapters 3 and 4, which are respectively devoted to the aggregation of MES for flexibility trading, and to market and regulatory perspectives.

- **For the studied MES, provision of flexibility is not their core business**. Therefore the priority of the MES operation is to satisfy the needs of their underlying physical process, e.g., supply heat or cooling to consumers for district heating and cooling networks, produce paper or steel, treat wastewater, etc. and their installations are initially designed and sized for these purposes. This can bring limitations to the flexibility that can be provided.

The installation or the increase of storage capacity (heat and/or cooling storage, steam accumulator, gas storage) provide a decoupling between the production and consumption processes for a given energy carrier and can significantly contribute to increase flexibility. This decoupling feature is not limited to the specific energy carrier associated with the storage device and can contribute to flexibility provision in the other energy carriers. The simulations of the scenarios implementing the improvement strategies showed that, depending on the case study, on the considered scenario, and the simulated week, increases of the available flexibility from a few percent (e.g., 6.5%) up to 250% could be observed.

The three figures below give an example of the results for the EMUASA case study. Figure 16 shows that the plant is able to provide mFRR (in red) in its base case configuration (scenario SC5). According to Figure 17, the introduction of a heat storage (scenario SC7) greatly improves its performance in terms of mFRR provision (in red). However, this is not the case with the increase (doubling) of the gas storage, as shown in Figure 18. In the EMUASA case study, introduction of a heat storage is therefore much more efficient than doubling the gas storage.

The simulations have also shown the introduction or increase of **storage capacity can reduce the MES operational costs**. However, a compromise has to be found, since oversizing may reduce profitability.

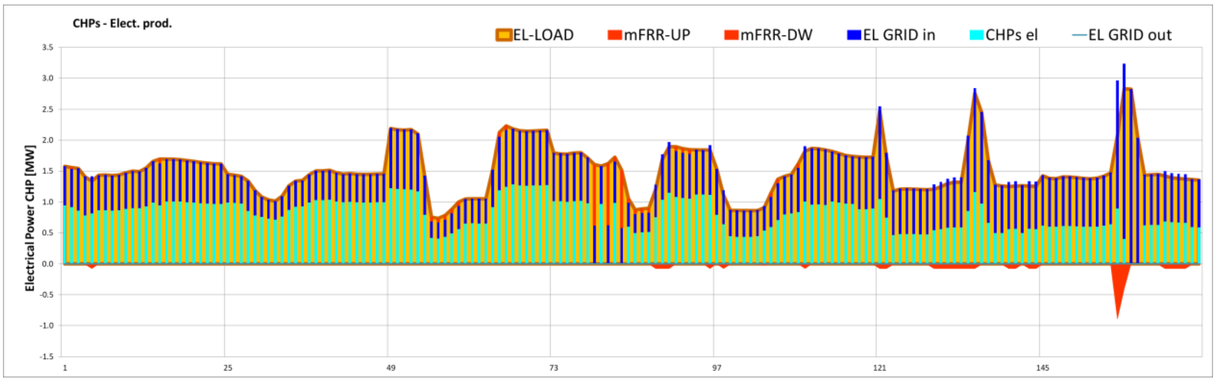


Figure 16 – mFRR provision in the base case (scenario SC5) for EMUASA in the winter season

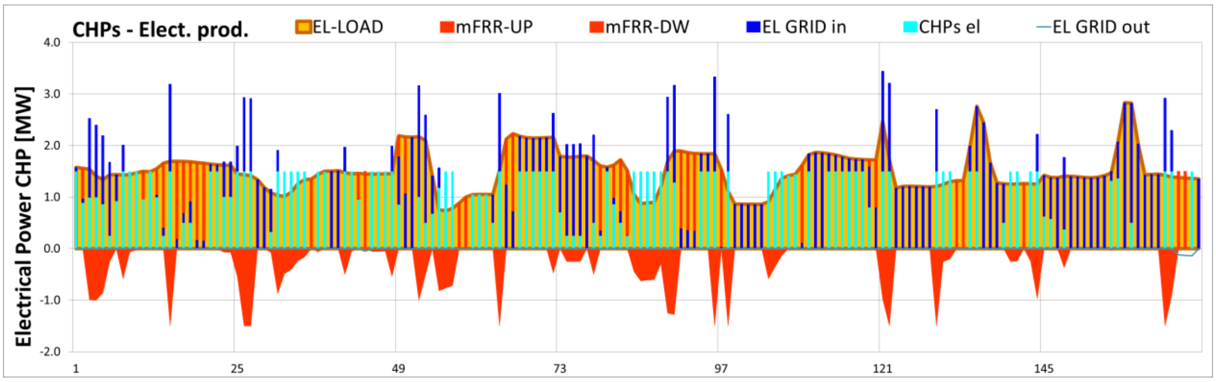


Figure 17 – mFRR provision in the configuration with the introduction of a heat storage (scenario SC7) for EMUASA in the winter season

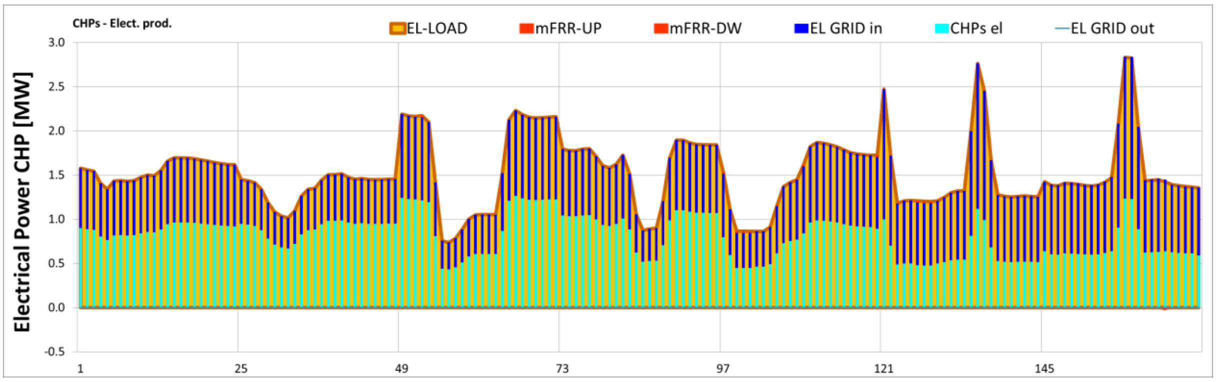


Figure 18 – mFRR provision in the configuration with the gas storage doubled (scenario SC6) for EMUASA in the winter season

As previously discussed, provision of flexibility affects the processes and operation of the MES, that have been optimized to meet the needs of its core business in the most efficient and economical way. The necessary changes or deviations in the operation plan cause a de-optimisation of the MES with respect:

- to the schedule of the technologies, and the more frequent use of more performing technologies with higher energy and operating costs might be needed. For instance, this is the case for the ACS case study with the more frequent use of the electric boiler.
- to the day-ahead energy market prices.

Provision of flexibility can lead to increased operating costs and MES will therefore participate in the only if the associated remuneration is sufficiently attractive to cover the additional costs. This topic is described in more detail in Chapters 4 and 6, taking into account not only the operational costs but also the capital costs and the aggregation costs. This is of course is an important factor of the business models presented in Chapter 6.

The results show that maximizing available flexibility often increases operational costs in the case studies. The difficulty to compensate the increased operational costs by the revenues from flexibility provision on the market is shown in Figure 19, which presents in percentage the changes in the coverage of the energy purchase costs by the revenues from flexibility provision with respect to the base case. Namely, the difference between the costs incurred to purchase energy (i.e. electricity, gas) and the revenues from the markets is computed and compared with the result obtained in the base case without flexibility provision (but including the revenue from the DA market). It can be seen that:

- For ACS the increased energy costs cannot be recovered.
- For Mälarenergi the increased energy costs are almost recovered. The difference is still positive but very close to 0.

- For the other case studies, the increased energy costs can be fully recovered but with very different levels: for the Austrian paper mill, the obtained value is very close to 0; for EMUASA, it is 3%; for HOFOR and NPT, the values are in between 15% and 20%; and Paris Saclay is a special case where the low level of available flexibility and the introduction of PV have a high impact in percentage.

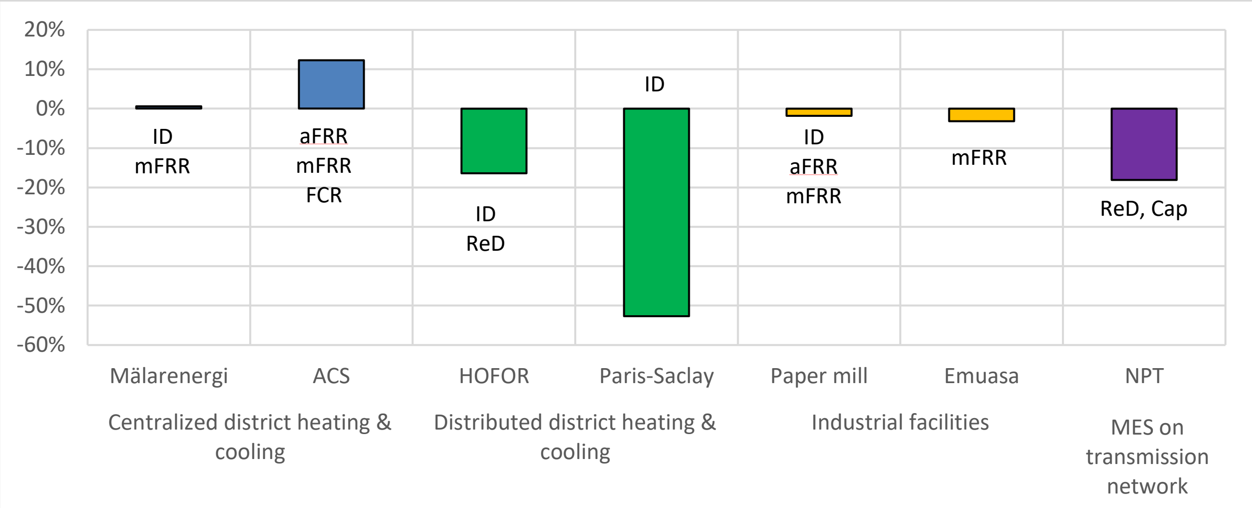


Figure 19 – Average change in the coverage of energy costs by the revenues compared to the base case

It should be noted that the low activation level of the frequency reserve services has a significant impact on the revenues. Indeed, in some countries like Italy or Spain, only the energy actually delivered is remunerated and there is no payment for the reserve capacity. Capacity payments for reserved flexibility as it is done in other countries, would improve the situation.

From the simulation results, it seems that optimization with respect to day-ahead energy market might often be more profitable than flexibility optimization. A more detailed analysis of the costs and revenues, the associated issues and the profitability of flexibility provision for the seven case studies will be presented in Chapter 6.

Energy consumption is an important factor in the costs and in the energy efficiency of the case studies. Figure 20 shows in percentage the average change in the energy consumption (electricity + gas) due to the provision of flexibility compared to the base case.

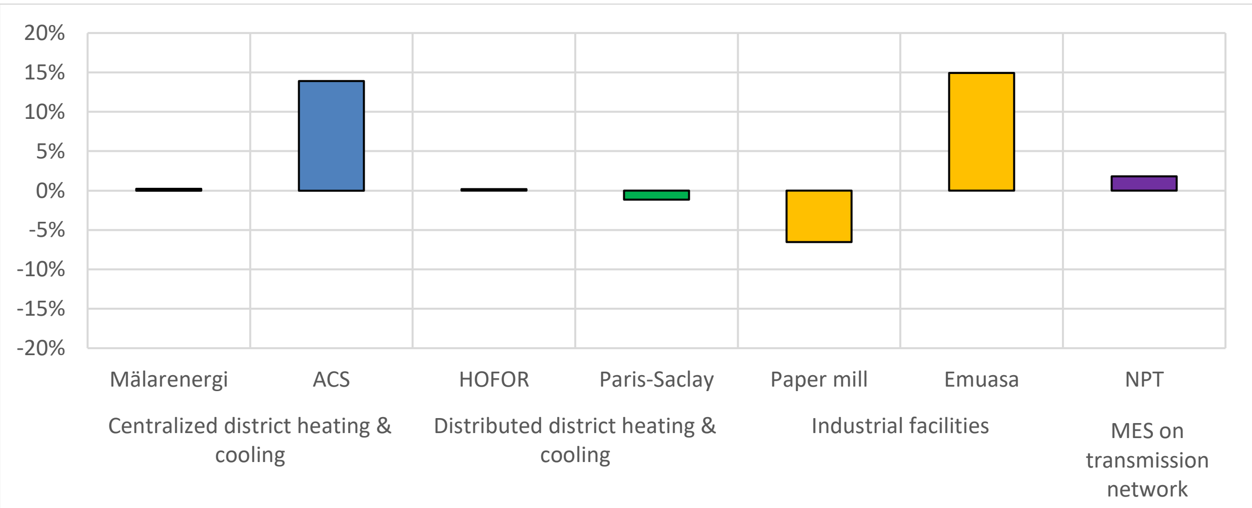


Figure 20 – Average change in the energy consumption compared to the base case

It appears that flexibility provision increases energy consumption:

- slightly for Mälarenergi, HOFOR and NPT,
- between 14 and 15% for ACS.

The energy consumption is reduced for the paper mill due to the installation of the steam accumulator which allows to avoid steam blow-off and save natural gas, and for Paris Saclay mainly due to the introduction heat/cooling storages in the substations.

More generally, the simulation show that the introduction of storage can reduce or limit the overall energy consumption.

The impact of flexibility provision on the environment was also evaluated by means of three KPIs:

- **Greenhouse gas (GHG) emissions**. Two types of GHG emissions are considered in the evaluation: direct emissions linked to the combustion of fuels in the MES and indirect emissions linked to the electrical consumption of the MES and the generation mix of electricity consumed from the grid.
- **The share of electrical energy produced by ren**ewables. The aim was to qualify the share of the electrical energy consumed by the MES, that was originally produced by renewables. This share can either come from renewable electricity generation (e.g. PV panels) or biofuel-powered CHPs present in the MES. In this type of calculations, the share of renewable electricity contained in the grid was not always included.
- **The share of energy consumed from renewable sources**. This KPI evaluates the share of renewables in the overall energy balance of the CSs including all energy carriers. It is used to indicate the amount of renewable energy consumed that cover the energy demand in the system. Renewable energy can be either electricity (tidal, solar, etc.), heat (geothermal, heat-pumps production minus electricity consumption, biomass) or gas (biogas production).

The impact on the GHG emissions was computed for all the seven case studies, whereas the other two KPIs were assessed only for those case studies for which they were relevant.

Figure 21 gives in percent the average change in the GHG emissions compared with the base case without flexibility provision.

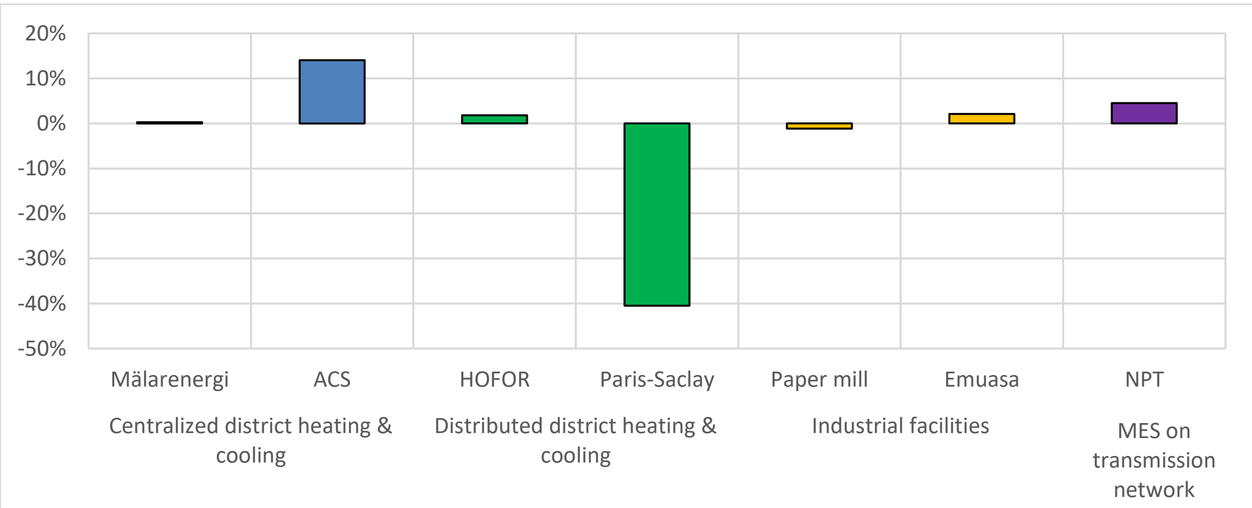


Figure 21 – Average change in the GHG emissions compared to base cases

It can be seen that **GHG emissions are generally increased because of the flexibility provision but the impact is limited** (between 0,3% to 5%), except for ACS due to the increased energy (gas and electricity) consumption (see Figure 20). For the paper mill, there is a small reduction (1%), while a significant reduction of GHG is observed for Paris-Saclay due to the shift from the use of gas boilers to heat pumps in winter and the replacement of grid electricity by locally generated PV electricity in summer.

All the MESs studied in the project use renewable energy resources to a certain extent:

- either directly, for instance biogas for EMUASA, geothermal energy and PV for Paris-Saclay, waste heat for ACS, solid waste which is considered 100% renewable in Sweden for Mälarenergi, red liquor for the paper mill,
- or indirectly through the electricity consumed from the grid depending on the electricity mix of the country, for instance HOFOR, the Austrian paper mill.

When the MES rely on renewable sources for their operation, the provision of flexibility may bring an environmental benefit to the grid by providing low-carbon flexibility.

Additionally, the increase in the share of renewables in the electricity mix will create a virtuous circle from an environmental perspective: when providing downward flexibility, the MES will indirectly import more renewable electricity and reduce their reliance on fossil fuels. The more the electricity supplied by the grid is decarbonized, the more downward flexibility will be environmentally advantageous. The opposite trend may however be observed for upward flexibility in some cases since electricity generated by some MES is still mostly resulting from gas consumption (e.g. in combined heat and power plants).

As a summary, the provision of flexibility by the case studies generally had a marginal impact on the energy and environmental efficiency of the multi-energy systems, especially when taking into account the introduction of the improvement strategies (e.g. thermal storages). In some cases, a larger impact could be observed due to the change in the scheduling of some energy devices (as seen for the ACS case study). Most often, activating positive flexibility will lead to increased energy consumptions (mainly natural gas), energy expenses and GHG emissions while the opposite trend in observed for negative flexibility provision.

Finally, **the seasonal nature of some MES operation** has to be taken into account, when considering flexibility provision. Seasonality is directly linked to the MES underlying processes. For instance, district heating and cooling systems show a highly seasonal nature with strong constraints for some seasons (for instance in summer or winter), but this may also be the case for other types of MES depending on their core business.

2.4.2 Recommendations

The simulation for each case study have been carried out for 6 (or 4) typical weeks of one selected year (2018 or 2019 depending on the case study), it would be useful to challenge the sensibility of the results by considering other years. This is particularly relevant for the economics aspects (costs and revenues), which depend on the market and electricity system conditions and change over time.

In the same way, it would be necessary to investigate to what extent the issues or barriers identified are specific to a national context or not, how different conditions would impact the results obtained.

More generally, deeper analyses are needed on the capability of MES to provide flexibility, the potential barriers, and success factors, for instance regarding:

- The flexibility capabilities at the level of the technologies.

- The best practices and best combinations of technologies and fuels to both meet the requirements of the MES and provide flexibility. For instance, combination of electrical boilers with renewable electricity production technologies and CHPs should be further investigated.
- Enhanced control and optimization strategies and ICT technologies to improve the integration of each technology.
- The integration of storage both at large and small scales, in particular in district heating networks. In this respect, further research would be needed on thermal storage, as well as support for its development.

Some recommendations on some specific technologies were also identified. Further research and development would be needed on:

- High temperature heat or steam storage, which are still at R&D stage, in particular heat storage at temperature levels above 300°C.
- High temperature as well as large-scale heat pumps, also integrating an objective of cost reduction.
- Low temperature heat networks, which appear very promising.

3 Aggregation of MES for flexibility trading

In this chapter, Section 3.1 first describes the software tools and processes developed for the multi-energy aggregation platform and for the trading of MES flexibility on the markets. Then the main outcomes and lessons learnt from their assessment and from the simulations carried out on the case studies (where aggregation is performed) are reported in Section 3.2, and finally, some recommendations are provided.

3.1 Aggregation platform tools and processes

As shown in Chapter 1 (Figure 2), the multi-energy aggregation platform plays a central role in the MAGNITUDE architecture for the trading of the MES flexibility on the energy and ancillary service markets. It was fully used for 5 of the case studies where the MES is connected to the distribution network, namely ACS, EMUASA, Mälarenergi, the Austrian paper mill, and Paris Saclay. In the HOFOR case study, HOFOR acts itself as an aggregator for the distributed units at consumers (i.e. heat pumps and thermal storages in multi-storey buildings, electric heat boosters and thermal storages in single-family houses) and only a part of the tools of the aggregation platform was used. In the NPT case study, both the CCGT and the steelworks are connected to the transmission network and it is assumed that they directly participate in the markets.

For each of the 5 case studies fully using the aggregation platform, the MES is integrated in a so-called aggregation pool with other Distributed Energy Resources (DER), characteristic of the national flexibility market participants. Typically, the aggregation pools consist of ten units of the following types:

- industrial CHP,
- "community supplying" CHP for district heating provision,
- renewable generation (run-off river hydro, hydro with pondage, wind power, photovoltaic),
- industrial demand response,
- other types of DERs, considered if there is an indication that certain technology is applied to a considerable extent in certain countries.

For each case study, the aggregation pool is built in such a way that the studied MES contributes for 10% to 30% to the total aggregated flexibility of the pool and the other technologies are represented in accordance with their weight in the national mix.

The aggregation platform is composed of several processes and tools, as shown in Figure 22, and the simulation workflow consists of 5 main steps described below [13], [14].

1. Forecasting of market prices and flexibility of the resources in the aggregation pool. Several tools were developed to carry out these activities [15], [16]:
    - Tools for the price forecasting of all the relevant markets for trading MES flexibility, namely intraday electricity, FCR, positive and negative aFRR, positive and negative mFRR. In addition, the price forecasts for the day-ahead markets of electricity and natural gas were also generated since they are used in the MES optimisation as explained in Section 2.4.
    - A data-driven flexibility forecasting tool for aggregation of large numbers of small technical units. In the project, the tool was developed for heat pumps, but it can be adapted to forecast the flexibility provided by similar distributed units, e.g. chillers or electric heat boosters.

- A practical method for the flexibility assessment of small energy storage units. This method enables a uniform description of many kinds of energy storage technologies, like thermal storage (heat, cold), steam storage, hydrogen storage or many more.

It should be reminded that the flexibility forecast of the MES considered in each case study is provided by the simulation and optimisation of the MES.

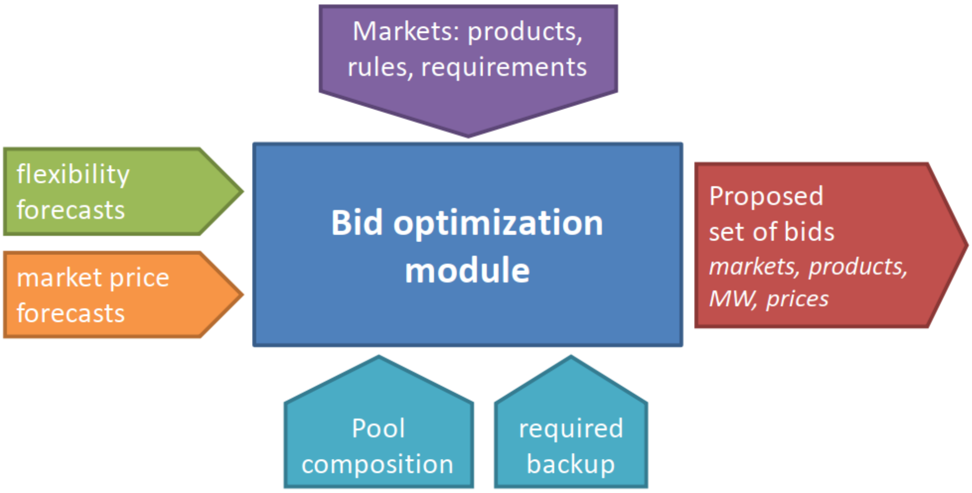


Figure 22 – The processes in the multi-energy aggregation platform [13], [15]

2. Optimization of the bidding strategy of the aggregated pool daily and generation of bids for flexibility in generation or consumption to be traded on selected markets. The following tools were developed to carry out the related necessary activities [15], [16]:
    - The bid optimisation tool, which uses the forecasts of market prices and of flexibility of the MES and other DERs in the aggregation pool, as well as more static inputs like technical characteristics of the MES, to perform an optimization of the flexibility allocation and bidding on the markets. The proposed bids and expected revenues are given for each considered market. The expected revenues per day are compared between markets, and the market with the highest revenue expectation is selected.
    - A tool for the management of uncertainties in order to optimize the required percentage of backup to be reserved in the aggregation pool, to face the risk of unavailability of the traded flexibility (because of forecasting errors or technical outages) and underperformance in provision of ancillary services, which may be sanctioned with high penalties. Since the different markets may have different price forecasts, different levels of penalties and different available flexibilities in the pool, the resulting backup rules are generated separately for each country and each market and taken into account in the bid optimisation tool.
3. Market emulation: a simple market emulator was developed to assess the acceptance of the generated bids on the markets. The market emulator simulates the market-clearing procedures by comparing the bid price, which was generated on the basis of a price forecast, with the real market price taken from a historic timeseries. If the bid price is lower than or equal to the historic market price than the bid is considered as accepted, otherwise it is rejected. Then as shown in Figure 4, the aggregation platform informs the MES about the accepted bids and the required reservation of flexibility, which can result in reserve (or capacity) payments in some markets.

4. Real-time operation and disaggregation of set points of the pool resources. The simulation of the real-time operation has two main objectives:
    - To provide the flexibility activation timeseries of the MES and the other DER in the aggregation pool. For the accepted bids, the activation setpoints on the different markets are computed based on the published statistics for the simulated weeks. The aggregation platform disaggregates the incoming setpoints and dispatches the units in the aggregation pool.
    - To enable, in the following step, the assessment of the revenues earned by the aggregation platform as a result of the activations and the energy delivered.
5. Financial settlement and distribution of revenues. In this final step, the aggregation platform calculates the performance of the MES and the other DERs in the aggregation pool and performs accordingly the distribution of the revenues.

In addition to the above steps, preparation activities have to be carried out before the simulation work can start, for instance:

- The collection of data and information on the procurement mechanisms and rules of the relevant markets (including rules for underperformance penalties), the traded product specifications and the historic time series of the market prices.
- The specification of the units in the aggregation pool, the collection of the appropriate data on their flexibility characteristics and associated costs, and the elaboration of their flexibility timeseries.

3.2 Aggregation of MES in the case studies

In the following, Section 3.2.1 first reports the main outcomes and lessons learnt from the assessment of the tools developed for the multi-energy aggregation platform and from the simulations carried out on the case studies where aggregation is performed. Then, recommendations are provided in Section 3.2.2.

More specifically, the simulation of aggregation and flexibility trading was performed for the case studies of the Paper Mill in Austria, HOFOR in Denmark, Paris Saclay in France, ACS in Italy, EMUASA in Spain, and Mälarenergi in Sweden. The simulations were performed with the objective to provide realistic results for revenues and profits of flexibility provision in different markets taking into account the national framework in the 6 countries. The markets investigated with the aggregation platform tools were intraday market for electric energy and the frequency ancillary services FCR, aFRR, mFRR, in accordance with the selected business use cases presented in Table 3.

As mentioned in the previous section, the simulation of aggregation and flexibility trading was based on forecasts, but the subsequent market emulation and simulation of service provision was based on real historic market data. The uncertainty about the market prices and about the actual activation of the ancillary services in the following trading periods was taken into account in order to generate realistic results for achievable revenues. This approach to use forecasts instead of historic prices is rarely used in scientific investigations because it requires a very high effort for data preparation and many additional simulation steps.

By means of the simulation approach applied in MAGNITUDE, it was possible to investigate the impact of several factors relevant for aggregation of distributed flexibility assets, such as:

- the required backup to be reserved within the pool,
- the minimum bid size and bid increment in the market,

- the revenue sharing ratio between the MES operator and the aggregator,
- the probability of activation in ancillary service markets, and
- the internal merit order dispatch of the assets in the aggregation pools.

3.2.1 Main outcomes and lessons learnt

The aggregation of a MES with other resources allows to trade its flexibility on markets that the MES alone would not be able to access. Through aggregation, a certain number of technological and market barriers can be overcome to different extents, for instance:

- Technical requirements of market products (e.g., maximum full activation time, the minimum duration of service provision, symmetric product) that are not compatible with the actual capability of some technologies.
- The backup required in some countries or needed to avoid penalties for underperformances in case of failure. An appropriate backup can be provided through an optimized dispatch of the resources in the aggregation pool. This will be discussed in more detail later in this section.
- Complexity of flexibility trading on markets (which show a very large diversity of rules and mechanisms in the different countries – this will be discussed in detail in Section 4.3.1) for MES operators, for which flexibility provision is not the core business.
- High thresholds for the minimum bid sizes and minimum bid increments in some countries for frequency ancillary service markets.

Regarding these thresholds, they are usually 0,1 MW on day-ahead and intraday energy markets, which has a limited impact on the tradeable capacity of a MES (except for very small units) or of an aggregation pool as shown in Figure 23 below. In frequency ancillary service markets or mechanisms, minimum bid sizes between 1 MW and 10 MW can be found in Europe and the minimum bid increment may vary between 0,1 MW and 5 MW (in many cases it is 1 MW). Figure 23 [8] shows for the Austrian case study the impact of the minimum bid size and increment on the percentage of flexibility that can be traded from the MES alone (denoted "case study" in the figure) or from the aggregation pool (denoted "pool" in the figure). Both provision of positive ("pos") and negative ("neg") flexibility is represented.

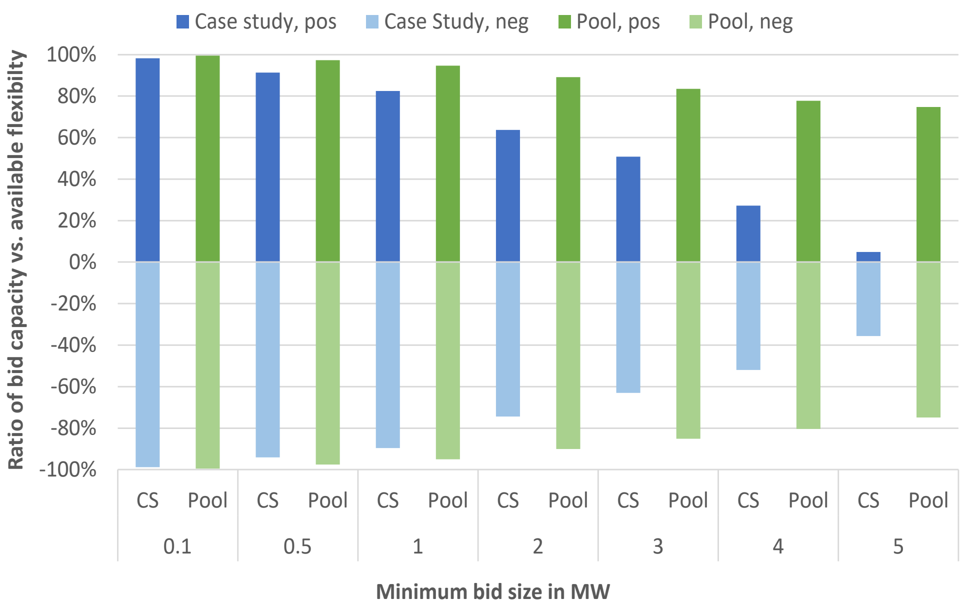


Figure 23 – Impact of the minimum bid size or minimum bid increment, for the Austrian case study [8]

It appears that a minimum bid size of 0,1 MW does not lead to significant losses of flexibility, while a minimum bid size and increment of 1 MW already reduces the percentage of tradeable flexibility by 10% for negative flexibility to 17% for positive flexibility for the MES, but only by 5% for the aggregation pool. And the reduction of the percentage of tradeable flexibility for the MES is larger and larger than for the pool when the minimum bid size/increment increases. This clearly shows the benefits of aggregation, which allows to significantly increase the share of exploitable capacity on markets with significant thresholds for the minimum bid size/increment.

But aggregation has a cost and it is assumed in MAGNITUDE that the revenues from the flexibility provision are shared between the MES and the aggregator to cover the costs of the aggregation platform and also ensure a revenue to the aggregator**.** In fact, the aggregation cost is shared between the different resources in the aggregation pool in the form of revenue sharing between these resources and the aggregator.

The percentage of shared revenues with the aggregator has a huge impact on the economic outcome of the MES and the aggregation. This is illustrated in Figure 24 for the Spanish case study. The left chart shows the investigation for the positive mFRR market and the right chart shows the result for the negative mFRR market.

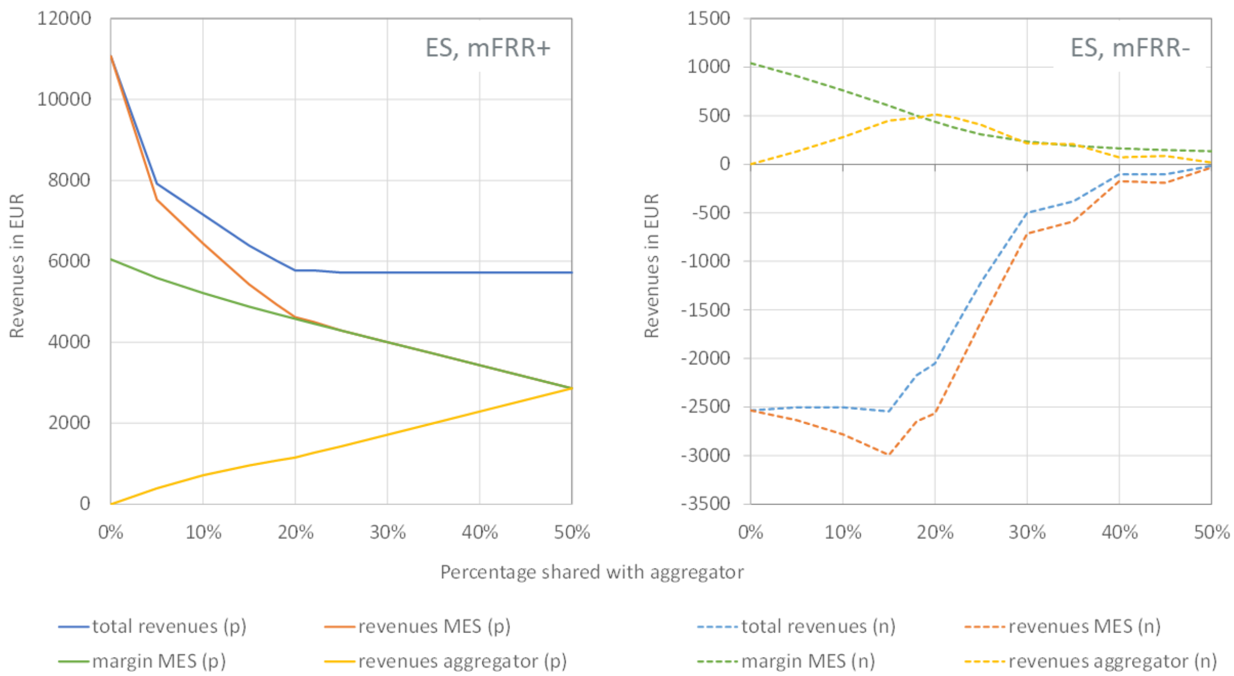


Figure 24 – Impact of the revenue sharing percentage between the MES and the aggregator for the Spanish case study

In the positive mFRR market, the marginal costs of the MES are close to the market price for about 40% of the bids but for the rest of the bids the marginal costs are much lower than the market price. If the revenues are shared between the MES and aggregator, the bid price must be increased in order to consider the part of the revenues shared with the aggregator. The figure shows that between 0% and 20% of shared revenues, there is a significant decrease of the revenues, because the increasing price of many bids exceeded the clearing price. Between 20% and 50% of shared revenues only bids with marginal costs much lower than the clearing prices remained and the increase of the bid price had a low impact on the acceptance of the bids.

In the negative mFRR market, the figure shows a different behaviour, since the marginal costs of all bids were in a similar range as the clearing prices. The MES imports additional electricity and has to pay for it. The bid price can be interpreted as willingness to pay for consumed electricity. Depending on the revenue sharing percentage, the MES additionally has to pay the aggregator or trader. Therefore, the bids prices must be lower than the marginal costs of the MES. With an increasing revenue sharing percentage, the bids become less competitive and at 50% revenue sharing the revenues get close to zero, i.e. only those bids which had an energy price of 0 EUR/MWh remained in the market.

So, the simulations show that, in the Spanish case study, the aggregator would receive the highest revenues with a 20% revenue sharing. Between 20% and 50% of revenue sharing the decrease of total revenues had more impact on the aggregator's revenues than the increase of the sharing percentage.

In practice, the MES and the aggregator can freely negotiate the revenue sharing percentage. The larger the amount of flexibility of a MES and the more reliably the flexibility can be forecasted and provided, the lower the sharing percentage will be in general. In the simulations carried out in the MAGNITUDE project, it was defined that 20% of the revenues are shared with the aggregator in all cases studies.

From this discussion, it can be summarized that that **the revenue sharing increases the marginal costs of the bids and can have a significant impact on the profitability of the case study.** This issue becomes crucial when the marginal costs of the MES are in a similar range as the expected market clearing prices.

On the other side, as previously discussed, the aggregation allows the MES to trade more flexibility and participate in more markets. The best compromise has thus the be found between the additional costs resulting from the aggregation and the benefits that it generates for the MES.

Another important aspect of flexibility provision is the probability of activation of the services (see also Section 2.4). In the case of day-ahead or intraday energy markets, all accepted bids must be delivered, so that there is no uncertainty about the expected revenues as soon as the bid is accepted (since the energy has to be delivered).

But the situation is different for frequency ancillary services, where there is a differentiation between the capacity or the power reserve procured to guarantee the availability of the flexible resources when they will be needed, and the activation of the service when the energy is actually delivered. The activation of the service by the TSO depends on the deviation of the grid frequency from 50 Hz, which follows a random distribution. The analysis shows that the actually activated power is in average much lower than the reserved power. In all investigated markets for ancillary services, in 2019, the activated energy was less than 20% of the maximum possible energy provision, i.e. the product of reserved capacity multiplied by the bid duration.

In some countries, the service is paid only for the energy delivered (activated) at the request of the TSO, so the associated revenues are very difficult to predict and there is a high uncertainty for the flexibility providers. In other countries, where there is a remuneration for the capacity (or reserve), the simulations showed that this capacity remuneration enhances the predictability of the revenues from ancillary service markets, and thus reduces the risk for the flexibility providers.

The simulations show that the flexibility provided by MES can be competitive compared to other technologies in the aggregation pool. This is illustrated in Figure 25 below. First it should be explained that the aggregation algorithms simulate the bid creation and internal dispatch of flexibility units in the aggregation pool according to the merit order, starting with the cheapest units. This approach resulted in different activation probabilities depending on the units' marginal costs. CHP units showed to be very competitive and could even provide negative flexibility at negative costs, because the reduction of generation led to savings in fuel consumption. On the other hand, renewable units (for negative bids in order to avoid curtailment) and emergency diesel (for positive bids) were sorted on the expensive (right) side of the merit order, where the dispatch probability is very low. As a result, those units were mainly used as internal backup.

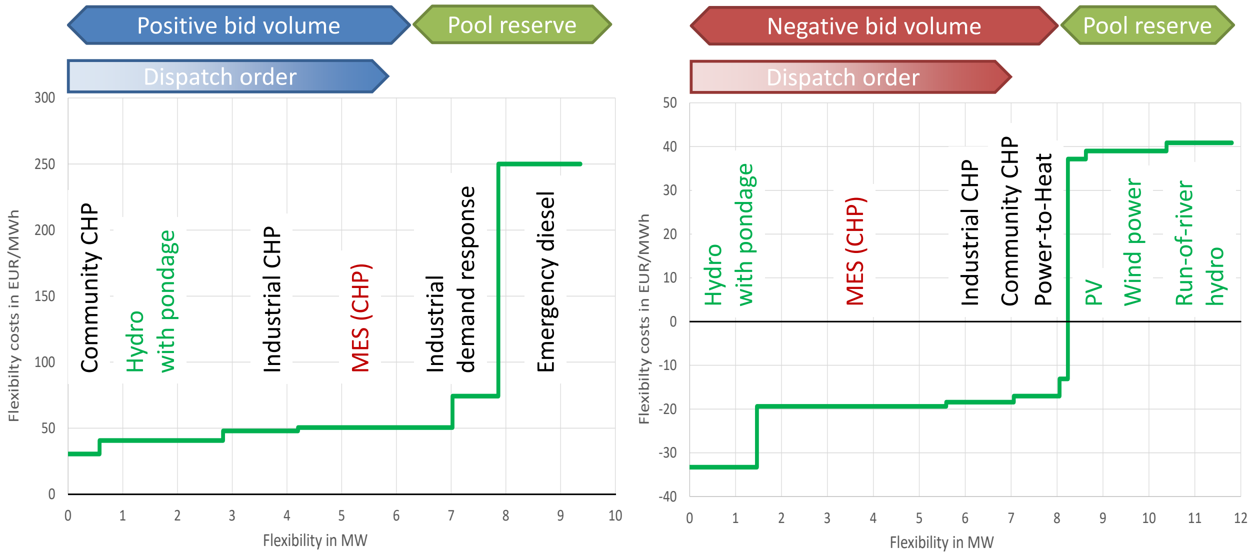


Figure 25 – Example of the internal merit order of the Austrian aggregation pool (averages of the timeseries over the six simulation weeks) [8]

The bidding strategy was assessed for the Italian case study **and gave results close to the best possible case in the ex-post analysis.** This is shown in Figure 26.

Some explanations are first needed. For the preparation of the trading simulation, the detailed market data (including distributions of prices and activation probabilities) had to be analysed. Based on the statistics of the previous months and forecasted market prices, the trading algorithm searches for an optimal bid price, at which the expected contribution rate of the accepted bids should be highest.

This optimization was performed separately for each simulated trading period, which was usually assumed as 1h, and the algorithm identified a bid price between the marginal costs and the maximum allowed price, where the highest contribution rate was expected. In the market emulation, the bid price (calculated based on forecasts and statistics) was then compared with the real market price, which decided upon the bid acceptance and the dispatch of the aggregators' bids.

The applied strategy was evaluated after the finalization of the market emulations for the six simulated weeks of the Italian case study and the results are shown in Figure 26 for the positive mFRR market in the figure at the top and for the negative mFRR market in the figure at the bottom. Both figures show the revenues, which would have been earned depending on the bid scaling factor. The bid scaling factor describes the factor by which the difference between marginal costs of flexibility and expected market price was multiplied and added to the marginal costs. A bid scaling factor of 0 means a bid price equal to the marginal costs and the margin is zero. A bid scaling factor of 1 means that the bid price is equal to the price forecast, which refers to ca. 50% probability of bid acceptance. In the case of the positive mFRR market, an average bid price of approx. 280 EUR/MWh would have provided the highest revenues and margin (circle on the figure) if the market behaviour would have been known beforehand. In the simulation, the algorithm selected an average bid price of ca. 260 EUR/MWh. This strategy earned a margin (or contribution rate) close to the best possible result in the ex-post analysis.

In the case of negative mFRR, the optimal bid price would have been close to 0 EUR/MWh, the selected trading strategy (which was determined based on statistics and forecasted prices) resulted in an average bid price of ca. 1 EUR/MWh, which is again close to the best possible case in the ex-post analysis.

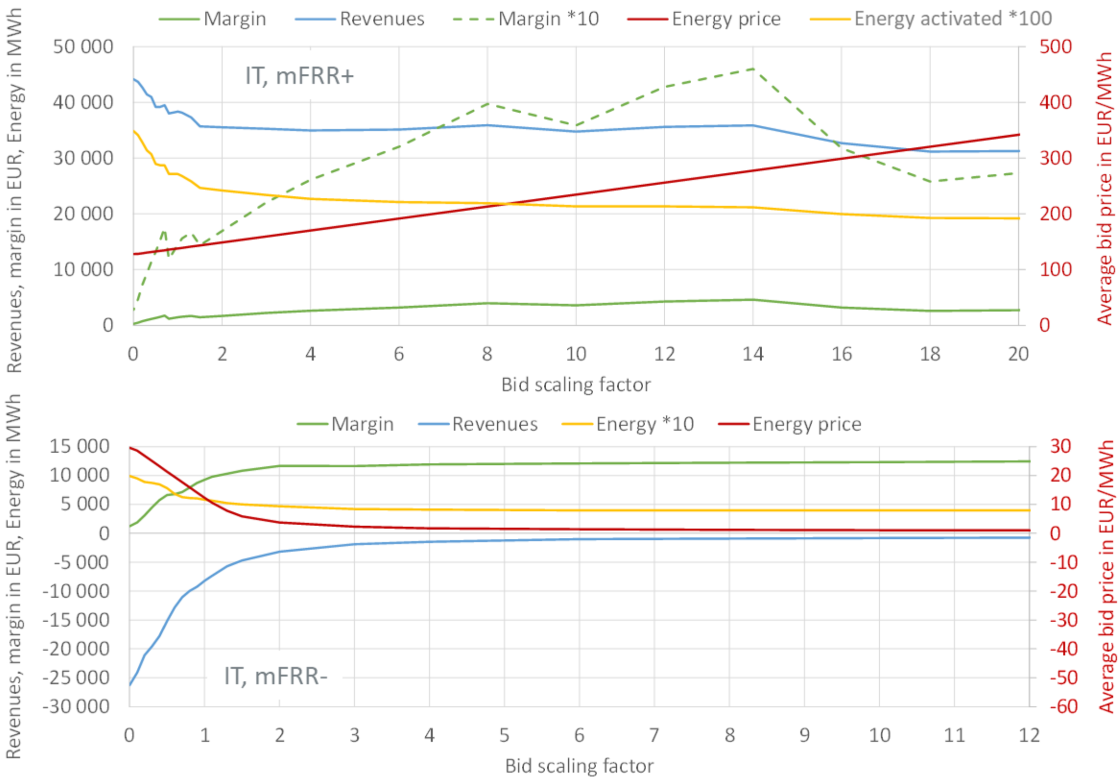


Figure 26 – Relation between average mFRR bid price and trading margin in the simulation of the Italian case study: for the positive mFRR bids in the figure at the top and negative mFRR bids in the figure at the bottom

Other lessons learnt on the trading of flexibility are given below but will not further detailed:

- It turned out that the markets in all six investigated case studies have very different rules and mechanisms, which did not allow a simple replicability of the algorithms for all six countries. This issue will be described and discussed in detail in Chapter 4. In these conditions, a comparison of the achievable revenues per MW between countries does also not seem useful nor relevant.
- It appears from the simulations that most of the 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.
- The results also 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.
- 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 (in particular for the intraday market), which promotes the conclusion that day-ahead optimization of the core operation is more relevant to MES than flexibility provision. The low revenues are also caused by a low activation probability for the frequency ancillary service markets. This low activation probability and the published bidding history of the entire market may motivate some aggregators or traders to apply bidding strategies with very high prices. This behaviour was observed in the simulations for

Italy and Austria. Finally, as previously mentioned, payments for reservation of capacities for ancillary services, can improve the amount and predictability of revenues for the MES.

- Too large threshold for minimum bid size and bid increment values may lead to reduced liquidity on ancillary service markets. Liquidity could be improved if the minimum bid size is reduced., for instance a minimum bid size of maximum 1 MW could support the market participation of MES.
- In the investigated scenario based on the years 2018 and 2019, the intraday markets did not provide significant price incentives for MES, as long as the product duration is the same as in the day-ahead market. The introduction of 30 min products could lead to more attractive price signals. Additionally, the still limited liquidity of the intraday market turned out to be another barrier for the exploitation of electrical flexibility from MES.
- Ramping constraints can prevent some MES including systems such as heat pumps to participate in FCR, aFRR and mFRR markets. For these MES, the ID market will be more interesting, provided that the market liquidity is sufficient.
- In some markets, the flexibility provider will be penalized for underperformance, therefore there is an economic trade-off to be found between trading the maximum amount of available flexibilities which bears the risk of penalty payments in case failure of one or more assets and a large amount of internal backup which reduces the market revenues from flexibility provision. If detailed technical rules were known, these were implemented in the aggregation platform algorithms. For instance, in the Austrian aFRR market, the TSO requires to maintain a (n-1) backup, meaning that the backup capacity of each flexibility provider must be at least as large as the largest technical unit in the aggregation pool. In the same way, when the penalty rules were known, the economic optimum of backup reservation was assessed by means of the tool for the management of uncertainties described in Section 3.1. Unfortunately, such rules could not be investigated for most countries. Then the minimum level for the penalty was assumed as the threefold of the market price of the hourly product. The optimization results showed that at this level the aggregator would have no economic motivation to maintain backup, because the probability of underperformance and penalization is lower than the loss of revenues caused by keeping internal backup. So, if the penalty is low, a profit can appear for a provider of flexibility that does not keep the required reserve capacity in the pool. On the other hand, high penalties cannot be supported because the margin is low in many markets.

Aggregation is a data driven activity which relies on the availability of different types of data and on forecasting of market prices and flexibility of assets. Several lessons were learnt in this respect:

- The simulation of a real trading situation including the uncertainty of clearing prices and the TSOs' orders for ancillary service provision is an innovative approach for a realistic assessment of revenues from markets for ancillary services or intraday energy. The quality of forecasts and statistical description of the market behaviour showed a direct impact on the achievable revenues. The main challenges were related to the large demand of detailed data about market rules and price timeseries, which led to far more effort for data preparation and simulation as initially planned. Reliable data and statistics were sometimes hard to find, as described below. In some cases, a more detailed analysis would have required additional input data which could not be provided due to confidentiality issues.
- Access to market data (e.g. market prices) and detail information about market rules (e.g. applicable penalty rules) is limited. And in some cases, market data have to be purchased at significant costs (e.g. EPEX prices).

- Forecasting of market prices is difficult. In particular, market prices of ancillary services are very volatile and difficult to forecast. For intraday markets, it appeared that DA market forecast is the best basis for the forecasts of ID products with the same duration (usually 1h).
- A data driven flexibility forecasting tool for aggregation of heat pumps and similar distributed units was developed (see Section 3.1). It may be difficult to accurately forecast the operation of one heat pump unit or one distributed resource due to diverse factors impacting on its operation, and the aggregation of numbers of units can help to even out the diversity of individual units. For this purpose, 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 forecasting. The results from the flexibility forecast show that the direction and period of flexibility usage depends on the operational characteristics of each individual pool of distributed resources. Therefore, continuous training with new data is required for the flexibility forecast tool to be used in different applications.

3.2.2 Recommendations

Most of the recommendations that can be provided based on the lessons in the previous section are in fact related to market and regulatory aspects. They will be presented in Chapter 4 (mainly in Section 4.3), which is devoted to these topics, and they will not be repeated here.

Some more specific recommendations are provided below, namely:

- Further investigations are needed on the tools developed for the multi-energy aggregation platform, and in particular the tools for the forecasting of market prices and forecasting of the flexibility of large numbers of distributed resources.
- In a more general way, further development work is needed to bring these tools to higher Technology Readiness levels (TRL), to adapt them to the current and future national requirements of the electricity and ancillary service markets in the different countries (taking into account the ongoing reorganisations) and to better support the requirements of aggregators and energy traders.
- Pilot projects would allow to validate the multi-energy aggregation platform software tools in a real multi-utility (electricity, gas, heat) environment. Additionally, such pilot projects that use real-time data would contribute to further assess the potential of the aggregation of distributed units to provide flexibility services to the electricity system.
- Further investigations are also needed regarding a more comprehensive assessment of the bidding strategies and possible improvements, as well as on the revenue sharing between on the MES and the aggregator. In particular, the simulations showed that when the marginal costs of the MES are in a similar range as the expected market clearing prices, then the revenue sharing agreement with the trader or aggregator might provide significant disadvantages for the MES. The impact of the revenue sharing should be studied more thoroughly and alternative mechanisms for remunerating the trader or aggregator might also be considered.
- First elements on competitiveness of the MES with respect to other technologies were provided through comparisons with the other resources in the aggregation pool in the merit order. More extensive studies are needed to fully assess the competitiveness of MES with both centralized and decentralized resources in the provision of flexibility to the electricity system.
- Finally, as previously mentioned, the availability or easy access to relevant market and technical data and information is a key factor for the aggregation activity.

4 Market and regulatory perspectives

In this chapter, the services to the electricity system that have been identified as most relevant to achieve the project goals are first presented in Section 4.1. Then some basic characteristics of the electricity, gas and heating/cooling sectors are given in Section 4.2.

Section 4.3 provides an overview of the main outcomes and lessons learnt from the detailed analyses carried out in the project on the existing market designs, regulation and services procurement mechanisms in the seven case study countries. Recommendations are also given.

Finally, Section 4.4 describes the innovative integrated multi-carrier day-ahead (DA) market designs that have been proposed to increase synergies between the electricity, gas, and heat markets, as well as the lessons learnt and recommendations on this topic.

4.1 Selected services to be provided to the electricity system

In order to identify the most relevant services that could be provided to the electricity system by MES to achieve the project goals, the main needs of the electricity system were first analysed in Deliverable D3.1 [2], as well as the different services that can be procured/provided to meet them. Three main categories of needs were distinguished: (i) needs of TSOs and/or DSOs, (ii) needs of States/policy makers (and subsequently also of TSOs), (iii) needs of energy sellers and buyers.

The most relevant services to be provided by MESs were then selected using the following criteria, namely selection of services:

- that allow to increase the share of Renewable Energy Sources (RES), and enhance the security of supply,
- for which the enhancement of the synergies between electricity, heating/cooling and gas systems provide real opportunities,
- for which the first elements already collected by the project (technical, regulatory, market design) showed a potential value for the provision by MES.

The resulting list of selected services is given in Table 6. It should be noted that the enhancement of the synergies between electricity, gas and heating/cooling systems will mainly have an impact on “energy” or active power in the electricity system, whereas it is expected to have a low (or even no) impact on the reactive power control. Therefore, the most relevant services are those services linked to active power.

For this reason, voltage control as such does not appear in Table 6. Indeed, in most cases, voltage control is a mandatory service being carried out by acting on reactive power at the connection point and then it depends on the reactive power control capabilities of the equipment/technology connected to the grid.

However, on the distribution networks, due to the technical characteristics of the medium voltage (MV) and low voltage (LV) lines, active and reactive powers are much more “coupled” than on the transmission networks, and active power control or re-dispatching can also be used to control the voltage at MV and LV levels, in combination with the management of power flow constraints. The management of distribution grids generally involves a combined optimisation process of the active and reactive powers on the grid to deal with both the power flow and voltage constraints. Active power control or re-dispatching is thus a flexibility service that can be offered to the Distribution System Operator (DSO) to meet its needs [17], [18], [19].

Table 6 – Selected electricity system needs and services (from MAGNITUDE Deliverable D3.1 [2])

System 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), Replacement Reserve (RR), and some 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 (ReD)
Energy trades - Reducing price risks and optimizing energy portfolios	Energy procurement mechanisms and markets: • Day ahead energy trades/market (DA) • Intraday energy trades/market (ID)
System adequacy	Capacity requirement mechanisms (Cap): • Capacity markets (together with other revenue streams) • Strategic reserves (without other revenue stream)

For the reserve services, two different aspects or phases must be distinguished: (i) the procurement of the power reserves in order to guarantee the availability of the flexible resources when they will be needed, and (ii) the activation of the service and the actual energy delivery. The procured reserves might indeed not be activated. This distinction may also apply to capacity services, as well as to some procurement mechanisms of local power capacities to be used for congestion management.

Other new flexibility services are being studied such as for instance ramping margin or provision of inertial response [20], [21]. However, they are not implemented yet in the MAGNITUDE case study countries. The characteristics of the products, the associated market mechanisms and remunerations still need to be clarified and no market data were available yet. So, they were not investigated in the project.

After the selection of the services presented in Table 6, the mechanisms existing in the 7 case study countries for their procurement were characterized in detail and compared in Deliverable D3.1 [2]. A description was also provided for the gas and heating/cooling sectors, which will be affected by such provision of services to the electricity system. More specifically,

- For the selected services, a comparative analysis of the associated electricity markets and/or service provision mechanisms was performed, including the following aspects: market mechanisms and regulations, products exchanged, remuneration and/or tariffs systems, main stakeholders involved and their key relationships.
- A comparative analysis was also carried out for the relevant market segments of the gas and heat sectors, covering to the extent possible the same types of aspects.
- Finally, existing or potential market and regulatory barriers that might affect the provision of the services were identified and described.

These analyses were carried out for the 7 case study countries, namely Austria, Denmark, France, Italy, Spain, Sweden, and the United Kingdom. However, for this latter only Great Britain is considered and not Northern Ireland. The main outcomes are summarized in the next sections of this chapter, completed with results from other deliverables such as Deliverables D1.3 [9], D2.1 [1], D4.3 [7], D5.4 [14], D6.2 [8], D3.5 [22], D3.2 [23], D3.3 [24].

4.2 Some basic characteristics of the electricity, gas and heat systems

The European electricity, gas and heat systems present different basic characteristics and different levels of development, which impact their respective market organization [2].

Electricity system

The product "electricity" is generally considered as a universal service or good, which implies a geographical coverage of the whole national territory and the continuity of service. Contrary to gas and heat networks, the electricity grid is then developed everywhere and is meshed at the local, national and supra-national scales to guarantee the system security.

Supply and demand of electricity are continuously varying, and the electricity storability presently remains relatively limited. The system operators are then obliged to implement complex real-time management of the power system to ensure the permanent physical match between supply and demand (i.e. balancing) and to maintain the system/network operational parameters within their optimal range (voltage, frequency, power flows, congestions, etc.).

There are four main categories of markets or mechanisms as already introduced in Table 6 in the previous section:

- The energy markets for the trading of electrical energy and which aim to reduce the risks (notably price and volume risks) of the market players (e.g. BRPs, producers, suppliers, aggregators, large industrial consumers) and enable them to optimize their energy portfolios.
- The frequency reserve and balancing markets for the TSOs.
- Service procurement mechanisms for network congestion management.
- Capacity requirement mechanisms, which exist only in some countries, and allow to cover the risks associated to future system adequacy.

Gas system

Natural gas is not considered as a universal product, i.e. there is no obligation to deliver gas in the whole country. For this reason, gas networks are not necessarily present in all territories of a given country. When there is a gas network, gas is transported via pipelines in the higher pressure (ca. 16-100 bar) transmission network over long distances and then in the lower pressure (ca. 1-25 bar) distribution networks over shorter distances to the consumers' premises. When there is no gas network, if natural gas is needed, it has to be delivered in another way (e.g. in container or barrels).

Natural gas systems present rather different national organizations, e.g.

- "Gas producing" countries (even if declining) with high market shares for natural gas (Netherlands, United Kingdom, etc.) vs "gas importing" countries as with lower market shares for gas.
- Highly integrated North-Western European countries (including Denmark, UK, Austria, and France) vs low interconnected ones (including Italy, Sweden, and Spain).
- Unequal distribution of underground gas storage facilities between countries in Europe: in 2017, 21 European countries cumulated 107,7 bcm, with 62 % of these capacities concentrated in Germany, France, Netherlands and Italy [25].

Operational restrictions and balancing mechanisms are also in place to ensure the security of supply when gas injection or withdrawal actions are undertaken. The pressure in the gas pipes is a key parameter that must be maintained between security levels indicated in the regulatory framework of each country.

Storability of natural gas is relatively easy. It first includes the volume of gas stored in the transmission and distribution pipelines – or linepack – up to a certain limit, and can also be achieved in liquid or gaseous form in over-ground storage facilities or underground reservoirs with storage ability depending on their type (volume capacity, speed to re-inject gas, etc.). Gas storage facilities enable to manage the gas system constraints such as seasonal and short-term balancing and the management of gas emergency situations.

Heating/cooling systems

Heating and cooling networks are inherently local systems, and present very heterogeneous situations compared to electricity and gas sectors.

It should be noted that district heating (DH) plays a minor role in the heat supply in most of the case study countries (below 5%), except in Sweden and Denmark (more than 50 %), where respectively district stands for more than 50% of the Swedish national heat supply and district heating is the most important heating source in the Danish residential heating sector (64.4% of all Danish households) [26]. A more detailed analysis shows very different situations in the considered countries:

- Around 200 urban networks in Italy and Sweden, slightly less than 700 in France mainly in urban areas; more extended DHs in Sweden and especially in Denmark.
- In the UK, because of the atypical British definition of DH including micro-DHs, a surprising gap is observed between their number (~5500) and the share of consumed heat they stand for (~2%).

District cooling networks exist in many countries, but they remain limited in number.

DH networks are generally poorly inter-meshed. Mainly based on urban networks, they are made of a set of non-cohesive networks except for some systems in Italy and Denmark. It also appears that although the potential for recovery of heat from industrial processes exists, interconnections between industrial heat networks and DH systems are still rare.

In terms of governance, heat networks are usually owned and controlled by local authorities. Local authorities are key stakeholders inasmuch as they are involved in the DH operation (through a public or private/public company) or in its supervision through public service delegation contracting. The role of national bodies can differ from one country to another (e.g., in France, non-national supervision of DH, regulation done at local scale).

Finally, the energy mix used for DH are very different from one country to the other, with for instance a RES share ranging from 12 % in the UK to 93 % in Sweden.

4.3 Markets, regulation, and service procurement mechanisms

In the first part, this section provides an overview of the main outcomes and lessons learnt from the detailed analyses carried out in the project on:

- the "global" designs and regulations in the three energy sectors, with a particular focus on the electricity sector and the market segments of the gas and heat sectors, which will affect or be affected by the provision of flexibility to the electricity system.
- The markets and mechanisms in place in the seven case study countries to procure/provide the relevant services presented in Section 4.1. For each market/mechanism, a series of features has been considered such as the eligible players, eligible technologies, volume thresholds, types and characteristics of products traded, mode of remuneration, etc.
- the facilitators, and market and regulatory barriers that might affect the provision of the services.

In the second part, recommendations are provided.

4.3.1 Main outcomes and lessons learnt

First, it should be noted that all three sectors share **structural similarities as network industries**, such as high fixed costs, long service life of assets, regulatory frameworks to control/monitor the implemented schemes and the interactions between networks and competing activities, management of network constraints, etc. The three sectors, and particularly the electricity and gas ones, need market or service mechanism designs with time horizons ranging from the short term (day-ahead and intraday) to the long term (years, quarters, months, weeks) [2], [1]. Balancing mechanisms are also needed but with different time constraints, in particular for the electricity system where closer to real-time activation aspects are crucial.

The same (or similar) global framework with three main phases for the energy or service procurement can be found in the three sectors as shown in Deliverable D2.1 [1] and discussed later in Section 7.1. These three phases shown in Figure 27 are the following:

- The planning and product procurement phase, including the identification of the needs, the formulation and submission of requests/bids, market clearing or bilateral/Over-the-Counter (OTC) negotiation, contract conclusion, etc. This phase may also require a prequalification of players to be able to participate in certain markets/mechanisms or to propose services.
- The product delivery phase, including activation mechanisms (depending on the service), physical delivery of the products, possibly real-time monitoring and measurement/metering, etc.
- The settlement or post-delivery phase, including exchanges of metered data, financial settlement, remuneration, cost recovery, possible ex-post penalties (in case of failure to deliver the contracted product), etc.

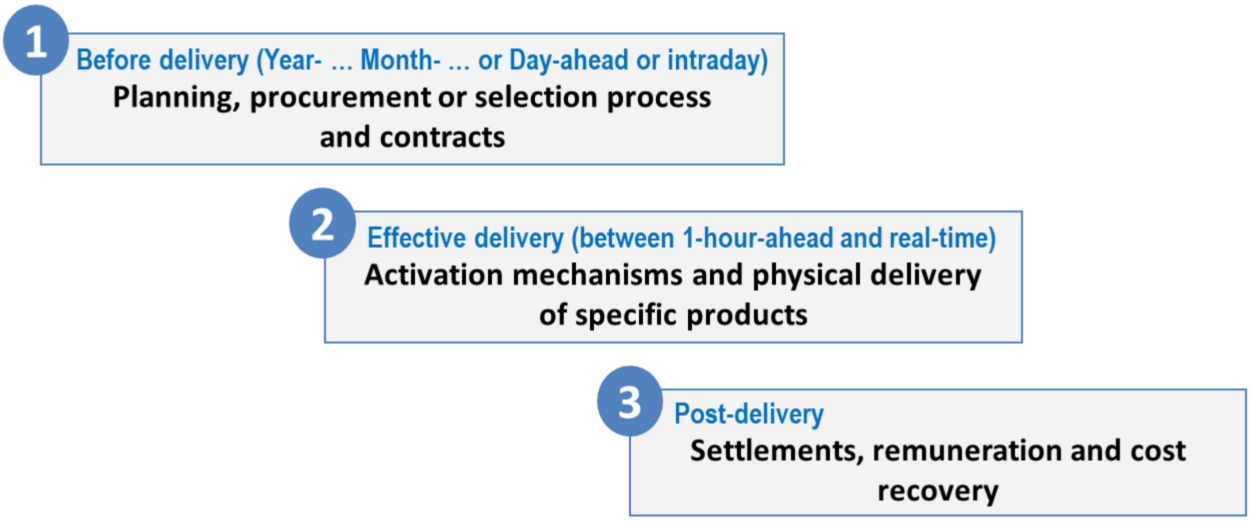


Figure 27 – The three main phases of the procurement process [2]

Beside the above-mentioned structural similarities, there are numerous differences of different kinds between energy systems, between countries and/or between market designs and regulatory rules.

Heat or cooling systems show the greatest diversity of situations, not only compared to electricity and gas sectors, but also between countries, between areas in the same country or even between one MES to the other, which may result from their inherently local characteristic, the type of governance and the absence of national regulation. This is also the case for their market design and regulatory aspects:

- Contrary to the electricity and gas sectors, there is no unbundling in the heat/cooling sector. The network roles may be carried out for instance by heat producers or suppliers, and not only by a dedicated DSO or TSO. The heat plant owner can be the DH network operator or just have a supply contract with the DH network operator (e.g., an industrial site owner selling its heat surplus or a waste recovery operator).
- There is no organized market as such, even if some sort of heat market mechanisms can sometimes be found involving a day ahead planning and intraday adjustments between the heat producers and the operator of the mechanism, like for the integrated heat market implemented in the Greater Copenhagen area in Denmark.
- Prices are generally set on the basis of a specific agreement between the private DH operator(s) and the local authority. Generally, heat suppliers do not have any nationwide pricing policy and there is no pricing regulation or monitoring at national or regional level unlike for gas and electricity. Prices seem to be set for every heat network taking local conditions into account, but they might have to be approved by the local or regional authorities in some countries.

In gas markets, an intermediate level of heterogeneity is observed between the studied countries.

- Bilateral contracts still in place for the long term.
- Beside OTC trading, most of the studied countries use the PEGAS/Powernext platform for day-head, intraday (or within day) and future products, which leads to similarities for the corresponding markets in the different countries. However, country specificities are still found in terms of the types of products traded and of the trading times. Many gas trading hubs are not yet mature and well established, despite of changes promoted by the European Commission (EC) to harmonise national rules via the implementation of four grid codes for gas since 2013.

- As for electricity, a balancing mechanism is required to ensure the quality and security of gas supply. As mentioned in previous section, it is facilitated by the easy storability of natural gas, at first in the pipelines themselves (i.e. line pack, permitting a short-term balancing within the day), then in storage facilities. The balancing mechanisms may take very different forms depending on the country, for instance:
  - constitution of balancing groups under the responsibility of a balance responsible party as in Austria,
  - balance obligation of the shippers and payment of imbalance payments such as in France and Denmark
  - balancing platform operated by the market operator for the trading of stored gas and of localised products as in Italy, or
  - procurement of normalised short-term and balancing products by the gas system operator and call for tenders as in Spain.
- Finally, the persistence of national cross border tariffs between countries inside the EU is perceived as a main trading barrier.

The electricity systems are still characterised by persistent national differences more or less important depending on the type of market scheme considered [2].

- Day-ahead and intraday energy markets are already highly similar in the considered countries, even if going further in the analysis, some country specificities can be found, regarding for instance the timelines involved or the product duration. Energy market coupling and/or transnational trading platforms are already in place and operated.
- A larger diversity is still currently observed for frequency control and balancing in the seven considered countries, e.g.
  - diversity of market mechanisms and product definitions: trading times, gate closure, ramping requirements and full activation time, bid duration, minimum bid size, etc.
  - different balancing models in place: central dispatch versus self-dispatch, proactive versus reactive dispatch, etc.

  Initiatives launched by TSOs are ongoing to harmonize the procurement of balancing and frequency regulation services and to support the implementation of the EC Guideline on Electricity Balancing [27], e.g. the FCR cooperation, PICASSO for aFRR, MARI for mFRR, and TERRE for RR [28]. They will progressively reduce this diversity in the future.

  It should be noted that the EC Guideline on Electricity Balancing may have a direct impact on MES participation, since it permits a better sharing of resources used by TSOs to always make equal generation and demand, and it allows new players (demand response, renewables, etc.) to participate.
- Regarding congestion management mechanisms, there is a very large diversity of approaches used in the different countries to manage congestions on the transmission and distribution networks, and it is often very difficult to get detailed information on these schemes. Nevertheless, the analysis shows
  - different "combinations" between the use of direct control of different types of resources and the use of market-based approaches to procure flexibility services for congestion management,
  - market-based approaches for congestion management (including "organised" markets and calls for tenders) are currently mainly used at TSO level, but some implementations or

projects are now emerging at DSO levels in some countries (e.g. the flexibility procurement platform set up in France [29] [30], some pilots of the CoordiNet project [31], etc.).

To improve the cooperation between TSOs in terms of congestion management, the Guideline on Capacity Allocation & Congestion Management (CACM) [32] strongly advocates more coordinated remedial actions by TSOs.

In the same way, a deeper cooperation between TSOs and DSOs also appears as a key point [33], [34], [35]. Different solutions to improve the DSO-TSO cooperation have been proposed and are tested in several pilots (see for example [36], [37], [20]).

- Capacity requirement mechanisms exist only in some countries and where they exist, they take very different forms: centralized or decentralized markets or mechanisms, capacity payments, strategic reserves, etc. Additionally, in some cases, the participation in the capacity requirement mechanism prevents the participation in other markets: for instance, participation in strategic reserve mechanisms often does not allow participation in any other market, whereas participation in capacity markets does not prevent participation in other markets and therefore other revenue streams.
- Finally, the European network codes and guidelines [38] have an important role to play in the harmonisation of mechanisms between countries. Currently 4 network codes and 4 guidelines are implemented, and 2 network codes are in preparation. These sets of rules are drafted to facilitate the harmonisation, integration, and efficiency of the national market designs in the European electricity market.

Limitations to the provision of flexibility by MES

- As explained in Section 2.4, in most cases, provision of flexibility is not the core business of MES. The priority of the MES operation is to satisfy the needs of their underlying physical process, e.g., supply heat or cooling to consumers for district heating and cooling networks, produce paper or steel, treat wastewater, etc. and their installations are initially designed and sized for these purposes. The results discussed in Section 2.4 showed that provision of flexibility may imply additional costs:
    - capital costs due for instance to the implementation of new equipment such as thermal or gas storage devices, to the installation of dedicated equipment for monitoring, control and measuring, etc.,
    - operational costs resulting from the “dis-optimization” with respect to the DA participation and deviations/changes in the operation mode, implying for instance the scheduling of more performing devices but with higher operating costs. However, this situation is not met in all the case studies: for instance, the Austrian paper mill was able to reduce its operating costs up to 3% when participating in flexibility markets [8].
    - aggregator’s costs for trading the MES flexibility on the markets (as discussed in Chapter 3).

  MES will therefore participate in flexibility provision only if the associated remuneration is sufficiently attractive to cover the additional capital and operational costs. The difficulty to compensate these additional costs by the revenues from flexibility services has been in some case studies has been discussed in Chapter 2 and is an important factor of the business models that will presented in Chapter 6.
- Due the large diversity of markets and service procurement mechanisms in the different countries as described above, flexibility trading appears to be highly complex for MES operators, for which flexibility provision is not the core business. Providing flexibility through aggregators or traders enable to overcome this difficulty but with an additional cost. Nevertheless, this large diversity is a

barrier to the replicability of the aggregation tools and processes, the bid optimization algorithms, and the business models. The comparison of the potential revenues and feedbacks between countries also appear difficult.

- With the current decoupling between the sequential energy carrier markets, imperfect forecasts can result in a loss of profit for conversion technologies, and lost opportunity for market participants. For instance, the result of the NPT case study shows that more coordinated gate closure times for the gas and electricity markets would increase the profits of the considered local MES [7], [8]. This aspect will be discussed in more detail in Section 4.4.
- There might also be limitations due to contractual clauses on the energy supply, namely the current supply contract between the MES site and its electricity/gas suppliers may specify peak load limits or peak load prices. The provision of flexibility services by a MES may violate these peak limits, then generating penalties, or increase the costs due to the peak prices.

Unfavorable conditions in market and service procurement mechanism designs. There are still some conditions limiting or preventing the provision of flexibility by MES in the energy and ancillary service markets or mechanisms.

- There are still restrictions on some technologies in some countries for ancillary services provision: for instance, the participation of demand or storage are not always allowed. In the same way, aggregation is not yet fully allowed in some countries [2].
- Relatively high thresholds can be found in some countries for the minimum bid sizes and minimum bid increments. For frequency regulation and balancing mechanisms, the minimum bid size is usually defined between 1 MW and 10 MW and the minimum bid increment may vary between 0,1 MW and 5 MW. As shown in Chapter 3, this may significantly reduce the tradeable flexibility of MES. As already mentioned, the simulations results [8] for the Austrian case study showed that increasing the minimum bid size and increment from 0.1 MW to 1 MW already reduces the percentage of tradeable flexibility by 10% (neg. flexibility) to 17% (pos. flexibility) and much larger reductions are obtained for higher thresholds. In this respect, Figure 23 has clearly shown the benefits of aggregation, which allows to overcome this constraint to a large extent.
- The clause of exclusivity imposed by some mechanisms, like the participation in strategic reserve mentioned above, may also limit the flexibility provision.
- As already discussed in Section 3.2.1, in some countries (like for instance in Italy [2], [7]), there is no remuneration for the flexibility availability (i.e. for the reserve or capacity reservation) for aFRR and mFRR services but only a remuneration for the energy delivered in case of activation of the service by the TSO. The revenues related to energy provision are then difficult to predict, because the TSO's need for service delivery depends on the deviation of the grid frequency from 50 Hz, which follows a random distribution. The analysis shows that the actually activated power is in average much lower than the reserved power. For the service provider, there is therefore no guarantee to be remunerated, which means an increased risk and uncertainty. Payments for reservation of capacity, as it is implemented in some European countries, improves the amount and predictability of the revenues, and thus reduces the risk for the MES.
- Another potential barrier to the participation of MES in the provision of flexibility services is the symmetry requirement for some products (e.g. for aFRR and FCR), namely the capacity committed for downward and upward services must be the same for "symmetric" products, whereas it may be different for "asymmetric" products. Provision of symmetric products may be technically difficult for

MES or even not compatible with the actual capability of some technologies. This might also lead to important additional operational costs so that service provision is not economically viable option.

- Finally, the simulation results have shown some issues with the intraday energy markets (ID) in some countries, where the participation provided very low or even no benefits. This is due to low liquidity of this market and/or insufficient differences between the day-ahead and intraday prices in the considered countries.

Unfavorable regulatory schemes

- **The unfavourable conditions for electricity compared to gas** are also a barrier to the provision of flexibility by MES. In this respect, the following aspects can be mentioned:

  Asymmetry of taxes between energies to the detriment of electricity. This observation is not specific to the MAGNITUDE project and has also been shared recently by the European Commission [39], [40][3]. This situation of the taxes, which are disconnected from the respective carbon content of the energies, may have a direct and negative impact on the MES provision of flexibility to the electricity system. The analysis for the Austrian paper mill case study shows that the energy *charge* for gas is by far lower than the charge for electricity, causing a disadvantage for the latter and penalizing the provision of flexibility in the markets [41]. As an example, Figure 28 shows the different components of the energy costs for electricity and gas for an industrial customer in Austria in 2019 [14], [8].

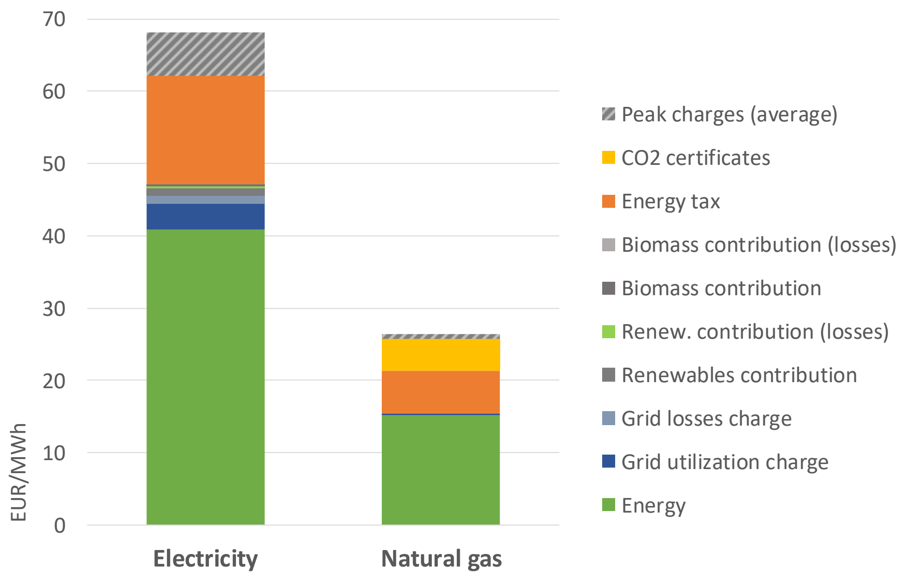


Figure 28 – Composition of an industrial consumer's energy price in Austria in 2019 [14], [8]

More generally, as shown in Figure 29 and Figure 30, EUROSTAT data (for small and large MES) show that in all considered countries excepted Sweden, the total amount of taxes and charges is higher for electricity than for natural gas both in absolute and relative values[4].

[3] The EC proposal for modifying the taxation of energy products and electricity was published on 14th of July 2021 [58].

[4] Except also for France in relative value in Figure 30.

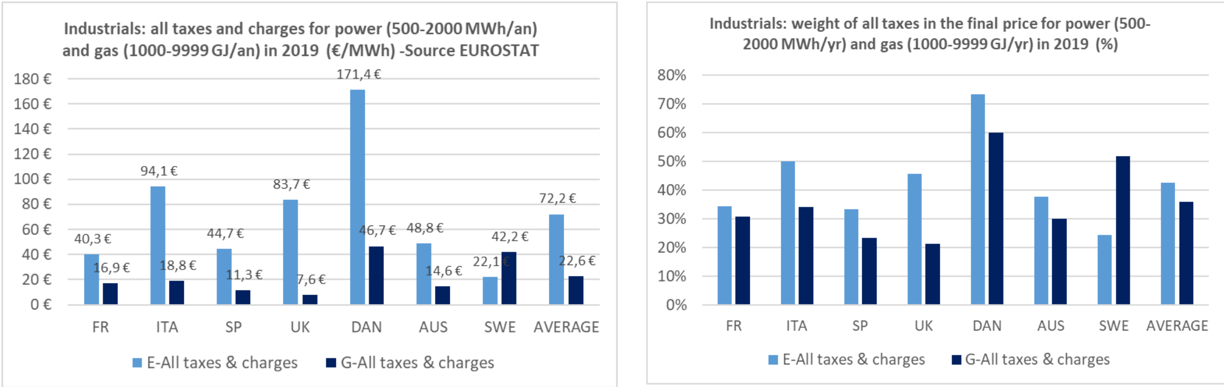


Figure 29 – All taxes and charges for industrial sites with energy consumption of 500-2000 MWh/year (electricity) and 1000-9999 GJ/year (gas) – Source EUROSTAT [42]

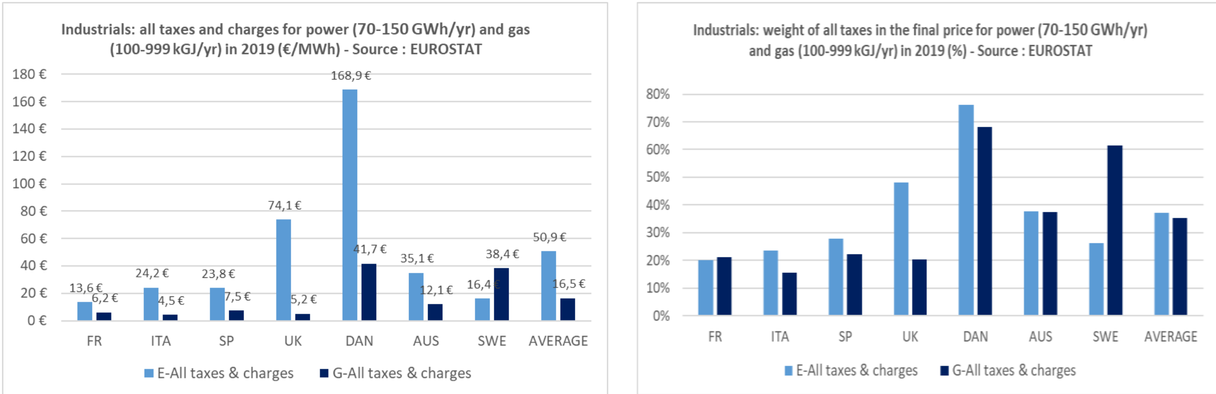


Figure 30 – All taxes and charges for industrial sites with energy consumption of 70-150 GWh/yr (electricity) and 100-999 kGJ/yr (gas) – Source EUROSTAT [42]

Grid tariffs higher for electricity than for gas in some countries. For instance, the analysis of the Austrian case study [41] mentions network tariffs for electricity more than 3-times higher than the network tariffs for gas. This is also illustrated on Figure 28.

More generally, Figure 31 and Figure 32 below show that this asymmetrical situation is shared by all the considered countries for the absolute values. The relative weights in the total final price are more contrasted: they are higher for electricity than for gas in Austria and Sweden for both types of industrial sites considered. In several countries (France, Italy, Denmark), the weight of network charges for electricity is lower than for gas for small industrial sites but higher for large industrial sites.

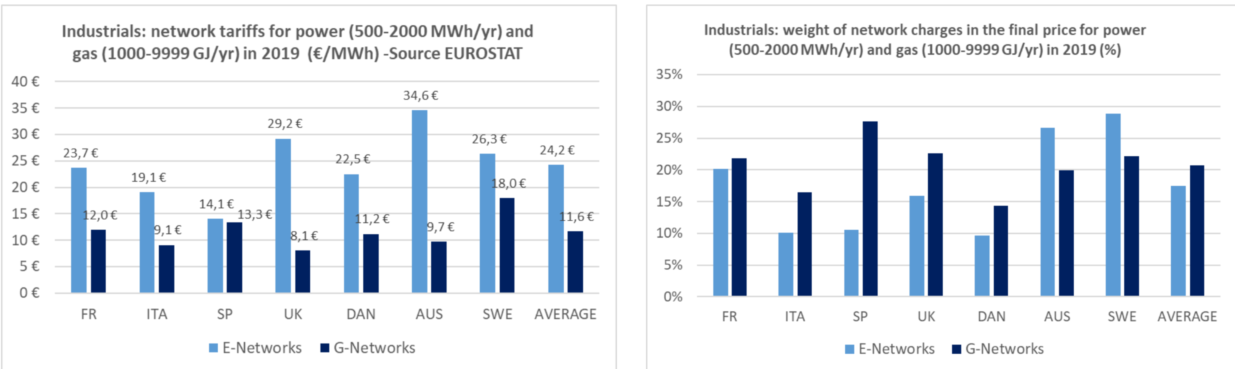


Figure 31 – Network tariffs for industrial sites with energy consumption of 500-2000 MWh/year (electricity) and 1000- 9999 GJ/year (gas) – Source EUROSTAT [42]

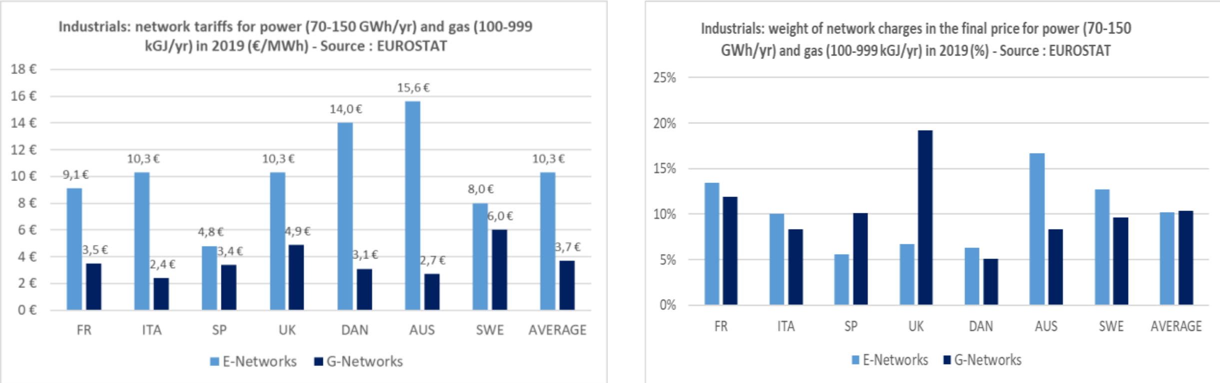


Figure 32 – Network tariffs for industrial sites with energy consumption of consumption of 70-150 GWh/yr (electricity) and 100-999 kGJ/yr (gas) – Source EUROSTAT [42]

- **Network tariff levels and structures** can be very different from one country to the other and may be determinant. Indeed, depending on their design (namely their level, the relative weight of fixed, energy and capacity terms, and possibly their time-based structure), they could be either a facilitator or a barrier for the provision of services by MES [2]. For example:
    - A high electricity grid tariff combined with a high energy component could be a real competitive disadvantage for power-to-heat technologies [43].
    - The peak load components of the grid tariffs contribute to encourage grid users' behaviors that are beneficial to the grid, but they might turn out to be barriers to the provision of flexibility services. Indeed, the provision of balancing and frequency regulation services might result in switching the consumption to peak or higher network price periods, or in exceeding certain thresholds, which lead to higher costs or penalties [41].

  In some countries, the awareness of these issues with network tariffs is raising. For instance, in Austria, the electricity network tariffs have evolved to significantly reduce the increase in the monthly capacity cost that may result from negative frequency regulation provided to the TSO [44].

- In the same way, **specific taxes or charges to support RES integration** that are added to the electricity prices might also provide barriers to the participation of MES to energy markets or ancillary services procurement mechanisms. An example is again given in [41] for Austria, where the RES contribution is based on energy and peak rates and penalizes the provision of negative balancing services.

- Further, in some countries, **renewable support schemes in other energy sectors may prevent or limit the provision of flexibility to the electricity system**. For instance, the regulation for DH usually fosters a high share of RES, waste, or heat recovery to reach environmental objectives. This may be done through dedicated support schemes without considering other possible objectives such as flexibility service provision. Some schemes impose minimum thresholds on the production of heat from renewables, and the provision of flexibility may require increased use of technologies that are not currently recognized as renewables in these schemes and may therefore be limited or prevented. An example is provided by the French case study (Paris Saclay), where providing flexibility services to the grid might decrease in some cases the share of RES used by the district heating network under the 50% threshold, and then exclude this DH from several support schemes (e.g. reduced VAT) and jeopardize its economic profitability.

- In several countries, there is **no clear regulatory framework to encourage DSOs to procure flexibility services** for their own needs on the distribution network, for instance to solve grid constraints, optimize the operation of the network, reduce network investments or defer reinforcement, and in some cases, the regulation does not even allow them to procure flexibility services from third parties. For instance, with a CAPEX-based regulation the grid operator would prefer investing in the grid rather than developing other alternatives. The implementation of a new balance between CAPEX and OPEX would be needed in the regulation of distribution networks to foster the exploitation of distributed resources' flexibility [45], [46].

Insufficient coordination between network operators

With the development of distributed energy resources in the electricity system and in particular in the distribution network, the issue of an increased coordination between TSOs and DSOs has been identified and is investigated in several projects, international working groups and other initiatives [33], [34], [35], [36], [47], [37], [20]. This coordination is essential to enable the provision of flexibility services by resources connected to the distribution grid, which is the case for a lot of MESs. The roles and needs of DSOs and TSOs are evolving and it is necessary to redefine their respective responsibilities and the way they interact. However, the solutions are likely to differ between countries, in particular due to the different structural organizations of distribution.

Another issue is the missing or limited coordination between electricity, gas and heat network operators. Increasing the synergies between the three sectors should not only be considered at market and regulatory levels but should also be investigated from a more technical perspective, for instance for network operation and sharing of technical knowledge and data. In this respect, it should be taken into account that electricity, gas and heat network operators have rather different system cultures and processes resulting from the different time constants, granularity, inherent resilience, and dynamic behaviors of the three types of networks. This topic is discussed in more detail in Chapter 7.

A very fast evolving field both at national and local scales

Market design and regulatory framework are fast evolving field: rules and mechanisms can change from one year to the other, or sometimes even faster. Participation in the markets thus requires taking into account their specificities and closely monitoring their evolutions both at the national and local levels. Access to the relevant information and adaptation to these evolutions may be highly complex, especially for small market participants or for MES for which flexibility provision is not the core business. This generally needs a dedicated organisation or support/services from players such as traders or aggregators. Some examples of difficulties can be listed:

- Public official documents detailing market designs are often very complex by nature, not presented in the way for the different mechanisms, and more or less easily accessible.
- Figures and data are sometimes very hard to obtain.
- The complex structure of the costs and tariffs for consumers make them difficult to understand even for MES operators.

4.3.2 Recommendations

From the previous section, it appears that the on-going harmonization activities of the market rules and mechanisms between countries (for instance FCR cooperation, PICASSO, MARI, TERRE) are important and needed. In the same way, the evolutions towards a level playing field for all types of technologies and stakeholders (e.g. generation, demand, aggregation, storage) should be continued.

Some improvements in the frequency regulation and balancing markets and procurement mechanisms would facilitate or encourage MES to participate in flexibility services provision, such as:

- Lower thresholds for the minimum bid sizes and minimum bid increments in some countries to enable MES to access more easily the market or to increase their tradeable flexibility.
- Payments for reservation of capacity and not only for the energy delivered (where this is not already the case), will allow to secure some revenues even when little flexibility is activated. As previously mentioned, this will improve the predictability of the revenues and reduce the risk for the MES.
- Provision of asymmetric products, which is technically more feasible for MES and more economically profitable than provision of symmetric products.

Still to facilitate the participation of MES, the discussion in the previous section also shows the needs for:

- An enhanced cross-sectoral approach to revise grid tariffs, energy taxes and renewable support schemes to better reflect the evolution of the energy markets.
- An improved cross-sectoral coordination between key players and markets, relevant for MES, in order to enhance the full exploitation of the local synergies between energy sectors. Increasing the coordination should also be considered from a more technical perspective, for instance for network operation and sharing of technical knowledge and data.
- An increased availability and/or easy access to regulatory and market information and data.
- Organization of knowledge sharing between MES projects could be beneficial, notable for small MES, for the access to both information and expertise on market designs. Additionally, the joint and concerted involvement of the various local stakeholders appears as a potential success factor for MES projets. Sharing knowledge and local experiences could become an efficient modus operandi of local energy transition projects.
- Finally, regulatory sandboxes could be implemented to test improved market designs and flexibility procurement mechanisms, and innovative market-based energy sector integration concepts in real-life.

4.4 Innovative market designs and market simulator

In the MAGNITUDE project, innovative day-ahead (DA) market designs have been proposed which allow to increase synergies between the electricity, gas, and heat markets. To this end, the concept of "multi-carrier markets" was introduced. In a multi-carrier market, dependencies (i.e., linkages) between various carriers are explicitly taken into account in the market products and the market clearing process [23], [24].

Five multi-carrier market schemes[5] were introduced and are shown in Figure 33. They are distinguished by the level of market integration (the chosen combination of single and/or multi-carrier markets) and the locality of markets (the existence of different local and/or global markets) [23]:

[5] A multi-carrier market scheme comprises a set of submarkets for day-ahead trading of different energy carriers.

- **MS1 - Single carrier energy market scheme**, in which only separate (single carrier) day-ahead energy markets are organised for the different energy carriers (gas, heat, electricity).
- **MS2 - Mixed single and multi-carrier energy market scheme**, composed of multi-carrier markets for gas, heat and electricity at the local level, and of single carrier markets for electricity and gas at the global level.
- **MS3 - Coexisting global and local multi-carrier energy market scheme**, composed of a unique multi-carrier market for electricity and gas at the global level and of multiple local multi-carrier markets for heat, gas and electricity at the local level.
- **MS4 - Local multi-carrier energy market scheme**, only composed of local multi-carrier markets for heat, gas and electricity.
- **MS5 - Unified multi-carrier energy market scheme**, composed of one unique multi-carrier market for heat, gas and electricity at the global level.

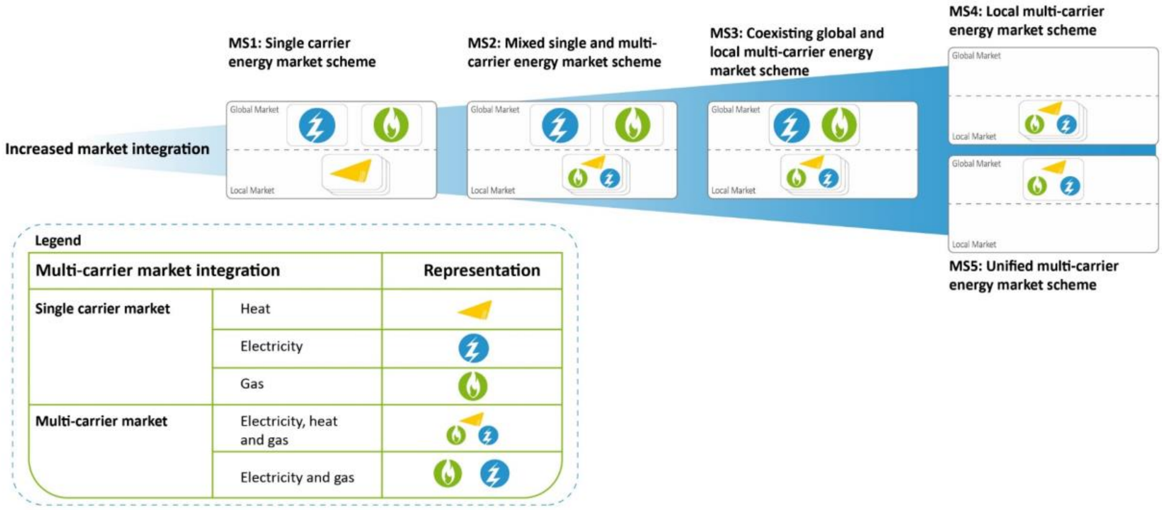


Figure 33 – Innovative schemes for multi-carrier markets

Among the five schemes, MS1 is considered to be a benchmark because it resembles most the current EU energy market design and MS5 is considered to be "the best case" concerning global welfare optimisation. For these two schemes (MS1 and MS5), four dedicated market designs and accompanying market clearing algorithms were then developed in the project [24]:

- **MD1.1 – decoupled multi-carrier market design with decentralised clearing** (Decoupled - Decentralised), where the separated markets for electricity, gas and heat are cleared in a decentralised way by their respective market operators. No explicit links exist between the three carrier markets and the impacts that the clearing results of the different carrier markets have on each other are fully internalised by the market participants in their positioning on the different markets.
- **MD5.1 - Integrated multi-carrier market design with centralised clearing** (Integrated - Centralised), where there is one unique integrated multi-carrier market for heat, gas and electricity at the global level operated by a single multi-carrier market operator. The market operator receives all the bids and offers for all the energy carriers and clears them centrally and simultaneously.
- **MD5.2 - Integrated multi-carrier market design with decentralised clearing with auxiliary variables linking the conversion orders** (Integrated - Decentralised - Variables), which preserves the current organisational structure with separate market operators for each carrier, while explicitly ensuring

the coordination between the different market operators through the exchange of appropriate information and the inclusions of dedicated (auxiliary) variables in their optimisation functions during the clearing process.

- **MD5.3** - **Integrated multi-carrier market design with decentralised clearing with an auxiliary agent processing the conversion orders** (Integrated - Decentralised - Agents)**,** which is a variant of MD5.2 where, instead of dedicated variables in the optimisation process, a new market operator role or agent is introduced to ensure the coordination between the three carrier market operators and is in charge of the conversion orders and constraints linking the cross-carrier orders (see below).

MD5.1, MD5.2 and MD5.3 are three proposed integrated day-ahead multi-carrier energy market designs, each with a different organisational structure, but we have shown that the same market outcome is achieved for all three markets if the information is exchanged among the market operators a sufficient number of times [24].

New market order types and constraints were introduced to design markets for MS5, which enable the market participants to buy and sell energy from different carriers explicitly and simultaneously. These orders and constraints help market participants to describe their technical and cost structures more accurately. They consist of conversion and time-shifting orders, and pro-rata, cumulative, implication, and exclusive constraints (Figure 34) [24].

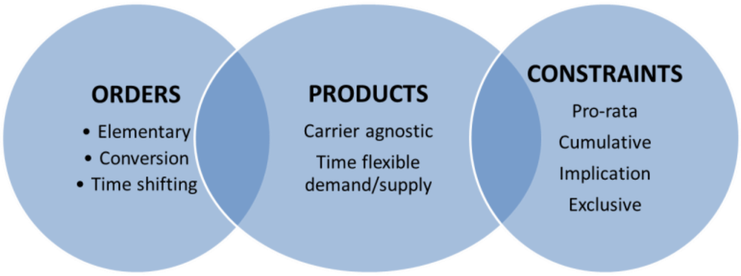


Figure 34 – Orders and constraints for integrated multi-carrier markets

A multi-energy market simulation tool was implemented in Julia [48]. It was used to assess and compare the MD1.1 (sequential) and MD5.1 (coupled) market designs for the bidding zone of Italy North, in the context of the ACS case study. It is described in Figure 35 below.

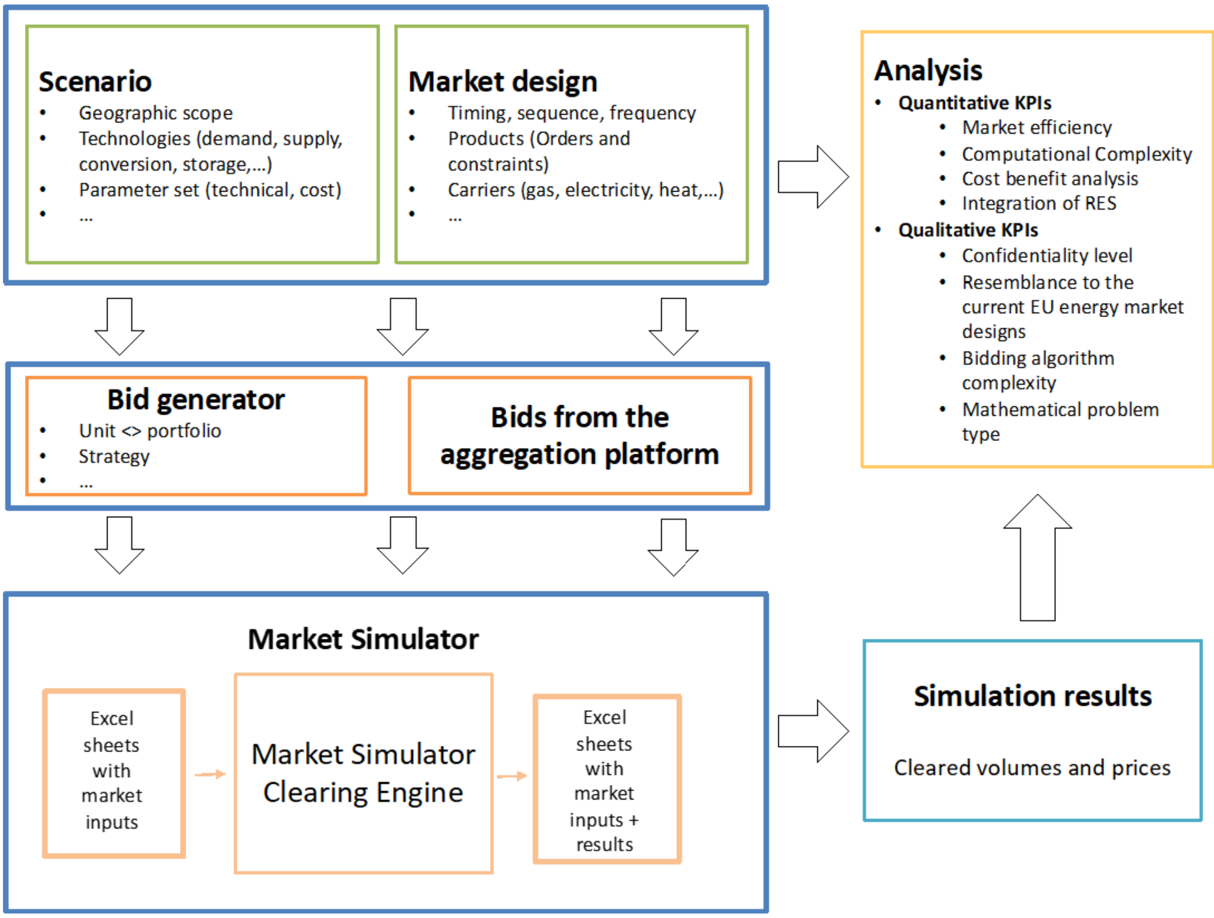


Figure 35 – The multi-energy market simulator

4.4.1 Main lessons learnt

Integration of different energy carrier markets is challenging due to the existence of physical and economic dependencies between the different energy carriers at different points in time. In particular, the physical coupling of energy carriers through physical assets such as conversion technologies is not straightforward to reflect on the different time scales of the market designs. If this physical coupling is not properly accounted for in the market design, the market outcomes are not guaranteed to be technically feasible or economically attractive for the market participants. The proposed integrated multi-carrier markets allow to take explicitly into account in the market products and clearing process such dependencies, which are not considered in the current market designs.

In the current decoupled sequential energy carrier markets, imperfect forecasts can result in a loss of profit for conversion technologies, and lost opportunity for market participants. In the integrated market designs, the new orders and constraints, and hence markets, externalize the market risk related to price forecasting errors of different markets and therefore decrease traders' sensitivity to such errors. Additionally, the novel orders and constraint types enable a better representation of cross-carrier or temporal flexibility in the market-clearing process and hence, automatic scheduling of such flexibility in the day-ahead markets. They allow market participants to better represent their technical limitations and cost structures, resulting in the elimination of technical infeasibility of a market outcome and higher social welfare.

Indeed, the simulation results of the comparison between the (benchmark) sequential market (MD1.1) and the coupled multi-carrier market (MD5.1) showed that the coupled multi-carrier markets:

- result in a higher social welfare as shown in Table 7,
- can better deal with situations when supply limits in any of the energy carriers are being reached,
- are better suited for achieving system reliability, as the flexibility in switching between energy carriers and within energy carriers over time is explicitly enabled in the market design, and
- are better suited for RES integration for the same reason.

Table 7 – Social welfare (€) Comparison - Coupled versus Sequential Markets

Social Welfare	Coupled Markets	Sequential Markets	Difference (coupled-sequential)
All simulated weeks	7.553.887.968 €	7.522.192.894 €	31.695.074

On the other hand,

- 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.
- An additional trade-off is in the increased information amount (such as conversion efficiency or the desired price spread) which has to be shared with the central market-clearing operator in coupled multi-carrier markets.

The implementation of the coupled multi-carrier day-ahead market designs will require organisation changes, which may be more or less significant depending on the underlying policy goals:

- If the aim is to preserve the current organisational structure of energy markets, with separate market-clearing operators for each of the carriers, the decentralised market-clearing MD5.2 could be implemented, despite the need for additional information exchange between the market operators. In this design, the market-clearing price definition is not straightforward.
- If slight changes in the current organisational structure are acceptable, the decentralised market-clearing MD5.3 with an additional market operator responsible for all the conversion orders and constraints, could be implemented. In this design, the market-clearing prices can be directly retrieved from the information exchanged among the market operators.
- If the information exchange among different market entities causes a computational time overload, and if sharing all the information with a single central entity is not an issue, a centralised market clearing (MD5.1) could be implemented.

The studies carried out show that the multi-carrier market framework and market simulator developed within MAGNITUDE can be used in two main ways:

- to conduct quantitative analyses of alternative market designs for an enhanced integration of day-ahead multi-carrier energy markets,
- to assess the value of introducing a new technology (including conversion or storage technologies) in the existing day-ahead market.

4.4.2 Recommendations

Further studies should be carried out on the potential benefits of the introduction of new order types (e.g. time shifting orders) in current markets, since they could leverage the flexibility potential of technologies with limited energy content such as demand-side flexibility or storage.

Beyond the conceptual work being done in the MAGNITUDE project, the comparison of the proposed market designs would require more thorough analyses, including Cost Benefit Analyses (CBA) taking into account not only the implementation costs of such market designs but also the impact on the transactions costs for all the stakeholders involved, before considering any real-life implementation.

In the project, market designs for only two market schemes were studied (Figure 33):

- MS1 considered as a benchmark, since it resembles most the current EU energy market design,
- MS5 considered as the best case, as it would lead to the highest welfare.

Further research should now be carried out on the other market schemes (MS2 to MS4).

5 Replicability of investigated case studies

A multi-disciplinary and cross-sector approach was used to assess the replicability and transferability of MAGNITUDE multi-energy systems (MES) and their business use cases to other countries and contexts. This chapter provides an overview of the main outcomes, lessons learnt and recommendations from this analysis reported in Deliverable D1.4 [49].

For the replicability assessment, the MES considered in the 7 real-life case studies of the MAGNITUDE project were associated to four categories:

- District heating and cooling networks: two high-temperature heat networks (Mälarenergi and ACS), an ultra-low temperature heat network (HOFOR), and a combined cooling and low-temperature heat network (Paris Saclay).
- Paper mills (Austrian paper mill).
- Waste-Water Treatment plants (EMUASA).
- Gas-fired plants (NPT).

The replicability was investigated for the 9 European countries represented in the MAGNITUDE consortium: Austria, Belgium, Denmark, France, Germany, Italy, Spain, Sweden, and UK. For this purpose, the current situation in each of the 9 States was analysed considering the following four layers:

- **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).
- **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 and 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.
- **Flexibility services**: the current characteristics (e.g. Full Activation Time, product deployment duration, minimum offer size, market product's shape, markets access and transparency) and the ongoing reforms of the selected flexibility services determine whether the MES are able to participate to the services and under what conditions.
- **Aggregation**: the possibility for aggregators to participate in energy markets/trade flexibility services allows decentralised installations, not reaching the size thresholds required for accessing the different markets, to participate.

The main outcomes and lessons learnt for these layers are summarized below.

Energy prices

Replicability of case studies, dealing with flexibility of power production from gas-driven CHPs / gas CCGT is favoured by a low gas-to-electricity price ratio. Such low ratios result either from low gas prices (e.g. missing CO_2 emission fees, lower taxation) or high electricity prices (e.g. through high taxes, or grid fees).

Replicability of case studies dealing with flexibility provision from heat pumps is favoured by a high heat-to-electricity price ratio: the lower electricity prices and the higher heat prices are, the more economically favourable are P2H technologies like heat pumps.

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.

Flexibility services and aggregation

As already discussed in Chapter 4, the characteristics of the flexibility services in each country show that current market designs in the different countries are widely diverse and driven by country-specific market environments. The main reason for the differences in balancing market designs is the historical electricity mix. It might still take years to effectively open all the markets to decentralized MES in all countries, with lighter and transparent pre-qualification processes.

The data availability is 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 helps 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.

In this respect, the roll-out of second-generation smart meters, broadband communication infrastructure, network remote control and digitalisation are very important to improve data availability.

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, Demand Side Response (DSR) is still mainly provided by large industrial plants, even if demand and batteries have a growing participation in different countries.

Technologies and Multi-Energy Systems

For district heating and cooling networks, the main factors for replicability are the overall electricity production from the plants connected to the DH networks, the gas-to-electricity as well as heat-to-electricity price ratios, the current average generation of district heating system (1st - 4th generation); the district heating increase in the last years, and the renewable share in district heating.

For pulp and paper mills, the replicability potential is directly linked to the self-production capacity. Within the pulp & paper industry, power-based applications such as chippers in chemical pulp production, grinders and refiners in mechanical pulp production, and pulpers and refiners in recycled fibre preparation are highly suitable for demand side management (DMS) applications. These units require high electrical power and controllability, and - similar to district heating networks - downstream storages enable the storage of the intermediate products and so the DMS potentials.

In wastewater treatment plant, the share of the sewage sludge utilisation for biogas production varies in the analysed countries. Not all wastewater treatment plants with a flexibility provision potential produce biogas so far, a mainly unused potential of flexibility.

Finally, gas-fired units play a different role across the analysed countries and have various shares in the overall electricity production. Natural gas is an increasing contributor to energy production in many countries. Average capacity factors show that gas plants are often well exploited. However, the situation improves if load factors are taken into account, the replicability potential is increased.

The next sections present in more details the main outcomes in terms of replicability for the four categories of MES, as well as for the layer on flexibility services and aggregation.

5.1 District heating networks

As previously mentioned, four MAGNITUDE case studies are related to district heating (DH) networks. Two are based on CHPs (Mälarenergi and ACS) and two (HOFOR and Paris Saclay) are related to low-temperature district heating with decentralised heat pumps. Replicability of such systems depends on multiple criteria, depending on the configuration of the considered MES.

For the case studies based on CHP production of electricity and heat, the heat produced is used for the district heating network (DHN), whereas the electricity is fed to the grid. The variation of the electricity production can be used to provide flexibility according to the MAGNITUDE use cases. However, the heat supply for the district heating network is a determining factor regarding replicability potential.

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 36, the best replicability potential is in Germany, thanks to the high share of CHP production in the DH sector. The potential in Austria, Denmark and Italy comes next, favoured by the low gas-to-electricity price ratio. France and Spain have a lower potential: despite large amounts of CHP production, the low electricity prices in combination with high fossil prices are a less favourable condition. For Belgium and UK, lack of data prevents an evaluation.

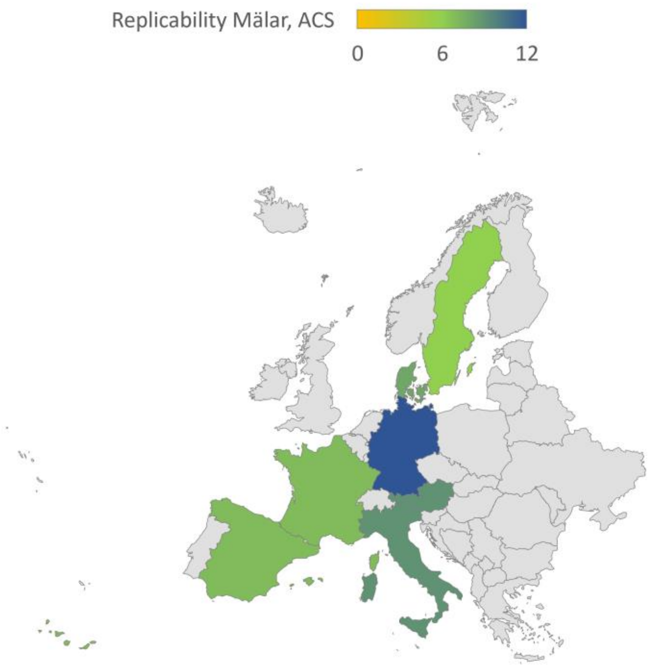


Figure 36 – Technical replicability potential of Mälarenergi and ACS case studies (based on the overall electricity production from CHP plants connected to district heating networks and the gas-electricity price ratio)

The two other case studies, HOFOR and Paris-Saclay are dealing with load shifting through heat pumps. Low-temperature networks are a key component of these systems, where one of the technical challenges is represented by cost-efficient heat pump integration.

Due to lack of data, a qualitative approach was adopted for evaluating the replication potential of low-temperature DH networks. The indicators used for the assessment include renewable share in DH, the heat-to-electricity price ratio, rate of increase of DH networks in recent years and type of DH generation.

As outlined in Figure 37, Sweden has the largest replicability potential due to its low-temperature networks and high shares of renewables. Next are France and Italy (due to the current growth of DH), followed by Denmark (due to the 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.

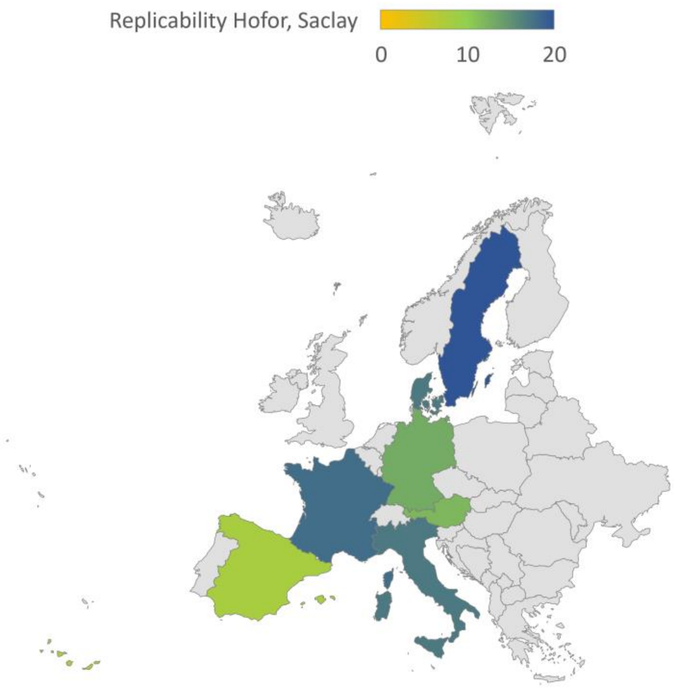


Figure 37 – Technical replicability potential of HOFOR and Paris-Saclay case studies, with distributed units (based on qualitative indicators: current average generation, rate of DH increase in recent years, heat-electricity price ratio and renewable share in DH)

5.2 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.

The replicability potential is directly related to the self-production capacity of paper mills. No data is available 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, and on the national shares of electricity self-production.

The flexibility potential of the paper and pulp industry was also calculated. As previously mentioned, within the sector, power-based applications (such as chippers in chemical pulp production, grinders and refiners in mechanical pulp production and 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.). As shown in Figure 38, 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.

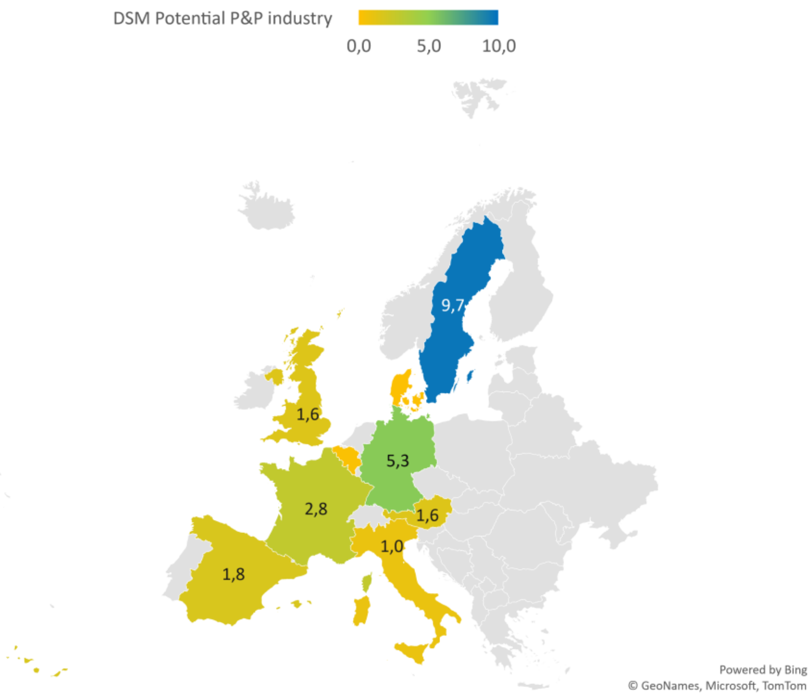


Figure 38 – Technical DSM potential for paper and pulp industry in MAGNITUDE countries [in GWh]

5.3 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 a number of WWTPs with a nominal capacity higher than 500 000 PE. There may be 144 urban waste treatment plants that could replicate outcomes for EMUASA case study and in total 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 of consuming it. Countries such as Spain, Italy and Germany have the biggest potential for replicability of EMUASA case study. 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.

5.4 Gas-fired Plants

Gas-fired 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 39 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.

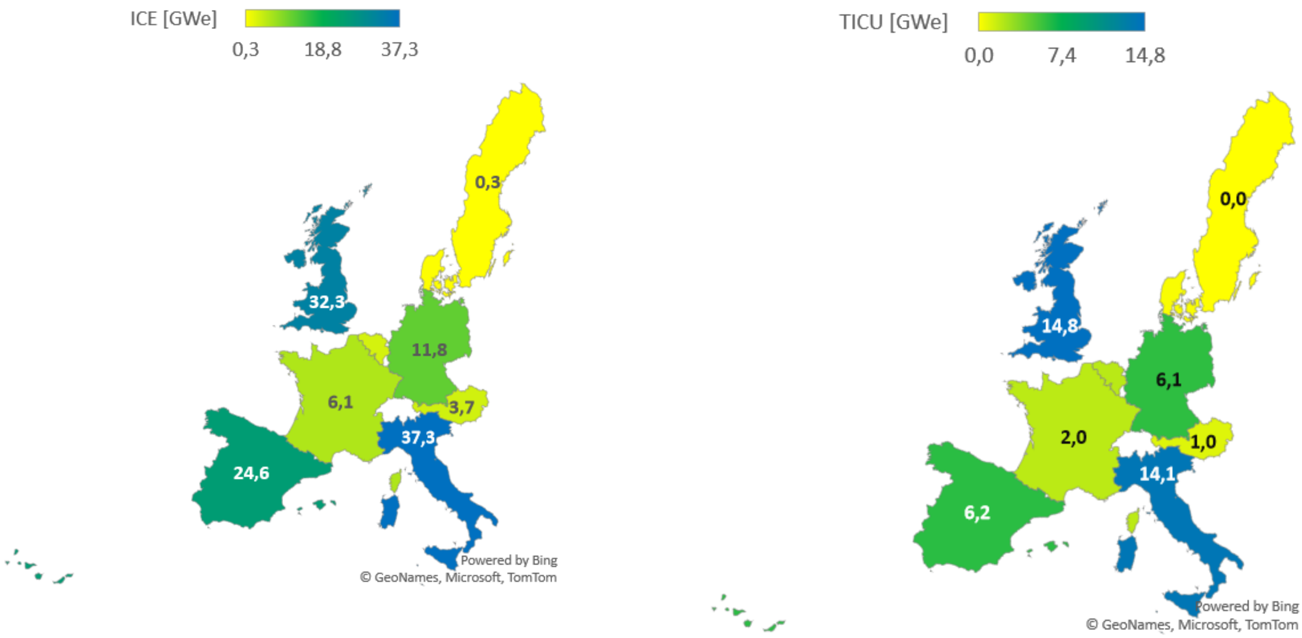


Figure 39 – Replicability of NPT case study (gas-fired plant) in the selected countries, left: total IEC, right: temporarily installed capacity utilisation (TICU).

5.5 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.

Figure 40 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 following indicators to assess the situation in the considered countries [49]:

- Possibility for Demand-Side Response (DSR), aggregated generation and loads to participate.
- Frequency of auctions and tender processes for products, and product durations.
- Technology neutrality: all technologies should have the possibility to participate, after having passed the pre-qualification process.
- Absence or presence of bidding restrictions or price limits (price caps and floors).
- Existence of a capacity requirement mechanism (CRM) open to MES.
- Procurement of balancing products through open and transparent markets or tender processes.

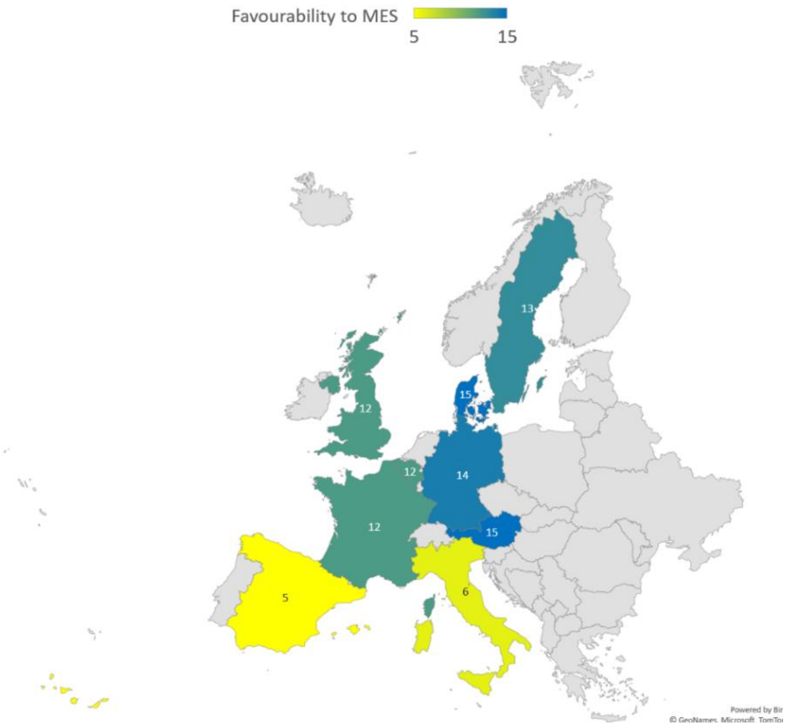


Figure 40 – Favourability to the participation of MES in flexibility services procurement mechanisms and markets

The figure shows that Denmark and Austria are the two most favourable countries. Germany and Sweden come next, closely followed by France, Belgium, and UK. In fact, the rankings for these 7 countries are quite close with values ranging from 15 to 12. Finally, Italy and Spain are the least favourable countries with ranking values of 6 and 5. They are currently facing several market reforms, but decentralised resources still have limited access to flexibility markets. A more detailed description of the results can be found in Deliverables D1.4 [49] and D7.4 [50].

From a use case perspective,

- **Pulp and paper mills**: the replicability for the Austrian paper mill, providing aFRR, mFRR and participating in the ID market, will probably give satisfactory results in countries where the minimum bid size is lower than in Austria, to ease direct market access (e.g. aFRR: Belgium, Denmark, France) or higher demanded FAT, to put less stress on technologies (e.g. aFRR: Belgium, France; mFRR: Belgium, Italy, Spain).
- **Use cases based on Paris Saclay and Hofor**: the participation to ID and DA 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 30-min or even 15-min products in DA and ID is also an advantageous condition, since fuel shift from DH to heat production by heat pumps is more easily sustained for short periods.
- **ACS use cases**: the provision of FCR, aFRR, mFRR by a CHP plant connected to a DH network, as in is most favoured by higher FAT and, possibly, procurement close to service delivery, to ease heat production (e.g. Denmark, Germany, Sweden).
- **EMUASA use cases**: the replicability of a WWTP like EMUASA participating in ID and providing mFRR, is favoured where minimum bid size for mFRR is lower than in Spain, to ease market access (e.g. 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).

- **Mälarenergi use cases**: the participation of CHP connected to a DH 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 (e.g. 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 for instance in Belgium, Denmark, and Italy (15 min, as in Sweden).
- **NPT use cases**: the analysis done about Neat Port Talbot cannot be replicated in countries where there is currently no Capacity Requirement Market. However, there are no particular limitations preventing the participation of large gas-fired plants to flexibility markets.

As concluding remarks, the following can be said:

- Market designs across Europe are still very diverse and driven by country-specific market environments. The situation is expected to change due the ongoing harmonisation initiatives.
- Currently, there is no "one" country which is the best for the replicability of all the case studies. Case-by-case assessment is therefore required for each business use case.
- Data quality and availability are key factors for replicability. Additionally, data collection and data representation are still very different in each country.
- In this respect, the roll-out of second-generation smart meters, broadband communication infrastructure, network remote control and digitalisation are expected to play an important role to improve the quality and availability of data.

6 Business models

The business models for the multi-energy system (MES) operators and for the aggregators were assessed for the provision of the services in the seven case studies as identified in Table 3.

More specifically, for 5 case studies (ACS, EMUASA, Mälarenergi, Austrian paper mill, Paris Saclay) the services are provided through an external aggregator and both the business models for the MES operator and for the aggregator were assessed. For the other two case studies (NPT and HOFOR), only the business models for the MES operators were assessed. In NPT case study, the services are assumed to be provided directly by the MES to the markets. In HOFOR case study, the MES operator aggregates the flexibilities of the buildings and single-family houses and carries out itself the role of aggregator for the trading of the services. The business model for HOFOR thus includes both aspects (MES operation and aggregation).

The economic viability of the identified business models for each of the cased studies was assessed based on a cost-benefit analysis. This assessment was done through a differential analysis of scenarios without and with flexibility services provision. Both cases without and with the implementation of the improvement strategies of Table 3 were investigated. Table 8 shows the scenarios that were selected for business model analysis in each case study [22]. It should be reminded that for all the case studies, the optimisation of the MES operation with respect to its participation in the DA energy market is always included even in the scenarios with "no flexibility service" provided (see Section 2.1).

Table 8 – Scenarios selected for business model analysis in each case study [22]

Case study	Scenario	Improvement strategies considered	Flexibility services provided
Mälarenergi (Sweden)	SC1	No improvement strategy	No flexibility service
	SC2		ID + mFRR
	SC3	Installation of a second heat storage	No flexibility service
	SC4		ID + mFRR
Paper mill (Austria)	SC1	No improvement strategy	No flexibility service
	SC2		ID + aFRR + mFRR
	SC3	Installation of a steam accumulator	No flexibility service
	SC4		ID + aFRR + mFRR
HOFOR (Denmark)	SC1	No improvement strategy - Domestic hot water (DHW) production for multi-storey buildings	No flexibility service
	SC2c	Implementation of external control of heat pumps and heat storages for DHW production for multi-storey buildings	ID + ReD
	SC3	No improvement strategy - DHW preparation for single-family houses	No flexibility service
	SC4c	Implementation of external control of electric heat boosters and heat storages for DHW preparation for single-family houses	ID + ReD

Case study	Scenario	Improvement strategies considered	Flexibility services provided
ACS (Italy)	SC1	No improvement strategy	No flexibility service
	SC5		FCR + aFRR + mFRR
	SC4	Increase of the heat storage capacity and heat demand peak-shaving in the winter season	No flexibility service
	SC8		FCR + aFRR + mFRR
Neath Port Talbot (UK)	SC1	No improvement strategy	No flexibility service
	SC2		ReD + Cap
	SC3	Change of the gate closure times for more coordinated gas and electricity markets	No flexibility service
	SC4		ReD + Cap
EMUASA (Spain)	SC1	No improvement strategy	No flexibility service
	SC5		mFRR
	SC4	Installation of a heat storage and doubling the gas storage	No flexibility service
	SC8		mFRR
Paris Saclay (France)	SC1	No improvement strategy	No flexibility service
	SC5		ID
	SC4	Installation of heat and cooling storages and PV electricity production	No flexibility service
	SC8		ID

The business model (BM) analysis implied two steps [22]:

- The qualitative analysis consisting in the identification and description for each case study of the following elements:
    - the value proposition of the BM (e.g. provision of flexibility services, without or with improvement strategies),
    - the beneficiaries of the service provision (e.g. market participants, TSO, etc.),
    - the key activities necessary to create value (e.g. optimisation and control, forecasting, etc.)
    - the key partners who contribute to the value proposition and the relationships between them (e.g. supplier, aggregator, etc.),
    - the required key resources, which can be physical (e.g. MES technological assets, ITC infrastructure), human (e.g. technicians, engineers, economists), financial (e.g. self-financing capacity, loans, etc.), or intangible (e.g. expertise, relationship quality, etc.),
    - the different channels used to make the value proposition accessible to the beneficiaries (e.g. market platform, communications channels, etc.).
- The quantitative analysis of the business models, which compares the differences in additional costs and revenues between scenarios with flexibility provision and their respective technological counterparts without flexibility provision. It consists in the description and calculation of:
    - All the direct and indirect costs components and their structure: capital expenditures (CAPEX), energy procurement costs (e.g. electricity, gas) and other operational costs (OPEX), associated with the provision of flexibility services and the relevant part of the improvement strategies.
    - The revenue streams of the service provision (e.g. revenue from the markets).
    - The positive and negative externalities which can have an impact on the BM (e.g. CO2 emission).
    - The financial cost-benefit analysis (CBA) and computation of the EBIT, annual cash flows, internal rates of return (IRR).

Several assumptions were made to carry out the quantitative analysis (in particular regarding values of costs, which are confidential in some cases). They are described in detail in Deliverable D3.5 [22]. Three important assumptions which may need to be challenged in further studies are listed below:

- It has been agreed among the MAGNITUDE project partners to use a 20/80 revenue sharing principle between the aggregator and the MES Operator, namely the MES operator keeps 80% of the flexibility-related revenue and the aggregator receives 20% of it for its market intermediation activity. Based on practical experience, this ratio could be between 10% and 50% and it actually depends on the negotiations and negotiation power between the MES operator and the aggregator. For instance, the larger and the more reliable a MES is, the lower can be the revenue percentage to be paid to the aggregator.
- For a profitable business model for flexibility service provision, the considered assumption is that a positive internal rate of return (IRR) must be obtained within 10 years.

In the following sections, an overview of the main results and lessons learnt from the business model assessment is first presented in Section 6.1. Then more specific results are provided for each case study in Section 6.2. Finally, some main recommendations are given in Section 6.3.

6.1 Overview of the main results and lessons learnt from the BM assessment

The economic viability of the flexibility service provision depends on two main conditions:

- the profitability for the MES operator, in the base case scenario (denoted by "B" in the table below), namely without the improvement strategy, or in the scenario with the improvement strategy implemented (denoted by "I" in the table below),
- the profitability for the aggregator, in the same scenarios (B) or (I). The profitability for the aggregator can be assessed using different approaches for the allocation of the costs between the resources in the aggregator's pool. Two main approaches were studied in the project:
  - An even allocation where the costs are evenly split among the different resources managed by the aggregator. In this approach, the same cost amount is allocated to each resource in the pool and the cost borne by any flexibility resource is the same whatever its size.
  - A flexibility capacity-weighted allocation, where the share of a given resource in the aggregator's overall flexibility capacity is the allocation key of the aggregator costs. Large flexibility resources then contribute to the cost coverage more than smaller ones, which means they are expected to generate revenues accordingly to their size.

The impact of the improvement strategies on the provision of flexibility services was assessed for each case study. The results showed that:

- most of the improvement strategies have their own business model as such, and the marginal impact on flexibility provision was assessed,
- some of the improvement strategies are dedicated to the provision of flexibility services.

Table 9 below displays the results of the profitability assessment of flexibility service provision for the seven case studies, as well as for both the MES operator and the aggregator (when relevant) in the two types of scenarios: base case scenario (B) and scenario with improvement strategy implemented (I). It should be noted that for HOFOR, the provision of flexibility services is not possible in the base case, and two scenarios with improvement strategies were considered: (I1) aggregation of the flexibility of heat pumps and heat storages in multi-storey buildings, and (I2) aggregation of the flexibility of electric heat boosters and heat storages in single-family houses (see Table 8).

Table 9 – Profitability of flexibility services provision for the seven case studies

	ACS		EMUASA		HOFOR		Mälarenergi		Paper mill		NPT		Paris Saclay	
	B	I (1)	B	I	I1	I2	B	I	B	I	B	I	B	I
MES Operator	N	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	N	y
Aggregator	Y	Y	N	Q	no ext. agg.		N	N	Q	Y	no ext. agg.		N	Y
Conclusion	**N**	**Y**	**N**	**Q**	**Y**	**N**	**N**	**N**	**Q**	**Y**	**Y**	**Y**	**N**	**Y**

Profitability	Y
Profitability questioned	Q
No profitability	N

(1) With a 90%/10% share of the revenue between MES and aggregator

In Table 9, the situations with a widely proved profitability are denoted by a "Y" in a green cell whereas those with a proved absence of profitability are denoted by a "N" in a red cell. It should be noted that situations with an internal rate of return (IRR) lower than 2% are considered as unprofitable.

There are a few so-called "questionable" situations denoted by a "Q" in an orange cell, for which it seemed difficult to come to a definitive conclusion at this stage:

- From the MES point of view, questionable situations occur when the profitability (Internal Rate of Return) turns out to be rather low (around 5%) and yet liable to be considered acceptable given other elements (e.g. positive image of an activity such as flexibility provision). Moreover, situations where the improvement strategy can only be justified when considering both the impacts on the regular operating costs and on the flexibility provision revenues are deemed as questionable. Indeed, inasmuch as the flexibility provision is not the core business of the considered MES in most cases, the MES operator might feel reluctant to be involved in an investment whose profitability depends on the output of an activity that it currently does not really master.
- From the aggregator's perspective, contracting with the considered MES for flexibility provision is deemed profitable if the IRR is significantly positive for both cost allocation methods described above (even allocation and flexibility capacity-weighted allocation). If that is the case with only one approach, the profitability is deemed "questionable".

Table 9 shows that flexibility service provision appears plausible in five situations:

- For ACS with the improvement strategy implemented (see Table 8) and when considering a revenue sharing of 90%/10% between the MES operator and the aggregator. Indeed, the calculations showed that for a revenue sharing of 80%/20%, no profitability could be found for ACS (see Section 6.2.1).
- For NPT (in which there is no external aggregator) for both scenarios.
- For HOFOR (who acts itself as an aggregator) for the improvement strategy 1, namely the provision of flexibility through the aggregation of the flexibility of heat pumps and heat storages in multi-storey buildings.
- For the Austrian paper mill with the improvement strategy implemented.
- For Paris Saclay with the improvement strategy implemented.

The sensitivity analysis carried out for ACS case study showed that economically viable business models could be found with a different revenue sharing between the MES operator and the aggregator. This might be the case for other case studies, too, and needs to be further explored. For instance, first investigations carried out for the Austrian Paper mill (in the base case) and EMUASA (in the base case) showed that a profitable business case could be found for both the MES and the aggregator through a higher share of the revenue for the aggregator.

Currently, the conclusions on profitability from both the perspectives of the MES operator and the aggregator are based on a flat rate of the aggregator's revenue of 20% applied to the income from flexibility provision. From the results of ACS (with improvement strategy), EMUASA (base case), Paper mill (base case), it appears that a discussion/negotiation between both parties (MES operator and aggregator) is needed to ensure that:

- There is at least one rate of aggregator's share high enough to ensure the aggregator's profitability, while providing a sufficient profitability of the flexibility provision from the MES operator's perspective.
- The actual cost allocation approach of the aggregator is compliant with a profitable contracting between both parties.

More detailed results and recommendations are provided for each case study in the next section.

6.2 Some specific results and recommendations for the case studies

6.2.1 ACS case study

In the ACS case study, the provision of FCR, aFRR and mFRR flexibility services is investigated. It should be noted that currently FCR is a mandatory service in Italy and cannot be offered in the market yet. In MAGNITUDE, the market-based procurement of FCR has been theoretically integrated in the simulations using price data from the French FCR service market and upscaling them by applying the ratio between French and Italian aFRR prices to the French FCR prices.

As mentioned above, with a revenue sharing of 80%/20% between the MES and the aggregator, the flexibility services do not provide sufficient revenues to compensate the additional costs related to their provision. There is no positive IRR and the earnings before interest and taxes are negative in both cases. With the improvement strategy (increased heat storage and heat demand peak-shaving in winter), the earnings are slightly less negative, which might be explained by the fact that more flexibility is now available in the MES.

Simulations showed that with a revenue sharing of 90%/10%, a profitability could be found for both the MES and the aggregator in the scenario with the improvement strategy. A more detailed sensitivity analysis is therefore needed to find the most appropriate value of the revenue sharing between the MES and the aggregator.

Without the improvement strategy, no business model could be found even with a modification of the revenue sharing between the MES and the aggregator.

The reason can be found in the fact that the provision of flexibility services requires ACS to operate its system in a different way, which generates increased or additional costs (in particular for the use of the electric boiler) higher than the revenues. The simulations show that, indeed, ACS receives positive revenues from its provision of flexibility services, but when analysing the cost of the entire system, the increase of the costs is larger than the revenues. Nevertheless, it appears that FCR brings along more benefits and higher revenues than the other ancillary services (aFRR and mFRR revenues are currently low). Therefore, a market-based system instead of a mandatory system for the procurement of FCR in

Italy would be beneficial for MES such as ACS, which could technically provide the service. More generally, to ensure that systems like ACS can participate in the provision of flexibility, the revenues from the ancillary service markets should be sufficient for the MES to recover their additional costs.

A more detailed analysis identified multiple reasons that explain why flexibility service provision does not lead to a positive business model:

- In case ACS provides downward flexibility, it imports more electricity from the grid. Yet, on these imports, ACS must continue paying taxes and tariffs, which further increases the costs.
- In Italy, there is no capacity remuneration for mFRR and aFRR, but only a remuneration for the energy delivered in case of activation. As a result, ACS is not remunerated for flexibility availability, even though its baseline costs are significantly increased to be able to provide flexibility. A capacity remuneration would increase the revenues and make them more predictable.
- The MES cannot earn revenues from the provision of negative flexibility since it is limited to an energy price of 0 EUR/MWh or higher.
- Even though ACS has a significant amount of available flexibility, as seen in Figure 14, the flexibility activated is less than 10% of the available capacity. In case ACS were activated more frequently, the business model would become more economically beneficial as there would be a higher likelihood that the revenues would cover the increased operational costs. This situation may change in future, with higher penetrations of renewable generation, which might cause higher needs for flexibility.
- The relationship between electricity and gas prices is unfavorable for the electric boiler usage as electricity is comparatively more expensive.
- The costs are further increased due to the aggregator's costs that come on top of the internal operational and investment costs for flexibility. This diminishes the margin even more.
- As already mentioned, FCR service cannot yet be offered on the Italian market. Although facilities such as the ACS MES, could technically provide it.

As a conclusion, on the one hand, it appears that the current Italian market for flexibility provision is not enough remunerative for multi-energy systems like ACS. To enable the exploitation of their flexibility, evolutions of the market and regulatory frameworks would be necessary.

On the other hand, further investigations are needed on ACS operation modes and optimisation to be able to provide flexibility in a "softer way" (e.g. with limited additional baseline costs, but less amount of flexibility), which could potentially lead to positive business models.

6.2.2 EMUASA case study

In the EMUASA case study, the provision of mFRR flexibility services is investigated.

In the base case scenario without improvement strategies (SC5 in Table 8), there is a profitable business model for the MES operator, but not for the aggregator when considering a revenue sharing of 80%/20%. Results of first investigations show that a business model might be found for both the MES and the aggregator by increasing the share of the revenue of the aggregator above 20%.

The scenario with the improvement strategies implemented (SC8) leads to a profitable but limited business model for the MES, because the revenues of the flexibility service provision have to finance the improvement strategies, which cannot reach profitability alone in ten years (the payback time of the heat storage and gas storage is more than 10 years). As for scenario SC5, it should be investigated if the increase of the share of the revenue for the aggregator above 20% could generate a profitable business model for both the MES and the aggregator.

6.2.3 HOFOR case study

In the HOFOR case study, the flexibility services investigated are services for congestion management on the distribution network (ReD) and participation to the intraday energy market (ID) (Table 3). Two improvement strategies are considered (Table 8):

- I1: aggregation of the flexibility of heat pumps and heat storages in multi-storey buildings,
- I2: aggregation of the flexibility of electric heat boosters and heat storages in single-family houses.

By construction, these two improvement strategies are generating the same flexibility potential of 1 MWel which is used by HOFOR as an aggregator to provide the ReD and ID services. The simulations showed that ReD services were providing 90% (for I1) to 100% (for I2) of the total revenues.

For improvement strategy I1, a profitable business model was found for both the MES and the aggregator, whereas no business case could be found for improvement strategy I2. These results could be explained by the fact that the total CAPEX and OPEX of the required equipment to implement the strategies are nearly the double for I2 compared to I1 for a very similar revenue.

The business model of I2 could however be improved through the identification and use of a low-cost solution for the external control devices.

As the revenues from ID flexibility services are very low, it would be worth to carry out additional simulations to explore other improved scenarios.

6.2.4 Mälarenergi case study

In the Mälarenergi case study, the provision of ID and mFRR flexibility services is investigated.

The simulations showed that the participation in the ID market is generating higher revenues compared to the mFRR market. As a result, all flexibility was offered on the ID market.

No profitability of the ID flexibility services could be found with or without the improvement strategy, mainly because these flexibility services require to start the electric boiler, leading to a high energy cost, which cannot be compensated by the revenues of the flexibility service provision.

The provision of flexibility services even has a negative effect on the GHG emissions balance of the Mälarenergi case study.

These results could be explained by the fact that the energy profile of the MES is already optimized on the DA market, and that the DA market proved to be more profitable than the ID one. In other words, it does not make sense economically to deviate from the optimal operation mode in order to enable flexibility provision. From a technical perspective, it is better to use the heat storage capacity entirely for the DA optimization than keeping a part of it for flexibility service provision.

6.2.5 Austrian paper

In the paper mill case study, the provision of ID, aFRR and mFRR flexibility services is investigated.

For the base case scenario, a profitable business model could be found for the MES but not for the aggregator. First investigations showed that to reach a profitable business model for both of them, it is necessary to increase the share of the revenue for the aggregator.

The simulations showed that the improvement strategy has a very quick payback of one year, it is increasing the profitability of the MES, and allows to find a business model for the aggregator for a revenue sharing of 80% (MES)/20% (aggregator).

The main benefit of the improvement strategy is related to energy savings, and the additional flexibility services options provide a minor contribution.

6.2.6 NPT case study

The NPT case study is composed of two MES, Baglan Bay CCGT and TATA Steel, which are part of the same area, but whose business models have been considered independent. For these two MES, participation in the capacity market and in the congestion management on the transmission network has been investigated without and with the considered improvement strategy (change of the gate closure times of the gas and electricity markets).

One of the positive impacts of these flexibility services is the reduction of RES curtailment

Without the improvement strategy, the provision of the flexibility services already generated a positive business model for the two MES, but with the improvement strategy, the benefit for the two MES is significantly higher.

The simulations showed the positive impacts of the improvement strategy for these two particular MES, but, as this improvement strategy is possibly impacting other market participants and in particular other MES, further investigations are needed to assess the impacts for other market participants and MES.

6.2.7 Paris Saclay case study

In the Paris Saclay case study, the provision of ID flexibility is investigated.

The simulations showed that no ID flexibility service was provided in the base case scenario (without the improvement strategies). This could be due to the fact that the electricity profile and costs were already optimized in the DA market.

The two improvement strategies are already generating a benefit for the Paris Saclay case study without any flexibility services provision, namely

- The installation of heat and cold storages alone has a payback of 8 years and an IRR of 5% after 10 years.
- The PV electricity production alone has a payback of 16 years and an IRR of 4% after 25 years.

The simulations showed that for these two improvement strategies the provision ID flexibility services generates a positive revenue and an IRR of 28% after 10 years.

6.3 Recommendations

The project results provided valuable insights on the aspects which have an impact on the feasibility of a business model for the MES and for the aggregator, and showed that profitability depends on:

- The regulatory framework, the rules, and mechanisms for the procurement of flexibility, such as the remuneration structure of the services, the grid tariffs, the energy prices and taxes, etc. Evolutions of the market design and regulatory framework should be considered to enable the full exploitation of the flexibility that MES can offer in the future electricity system with more renewables. This has already been discussed in detail in Section 4.3 and will not be repeated here.

- The operation and optimization strategy of MES to provide flexibility, which can lead to higher direct and indirect costs. In this respect, further detailed investigations of alternatives approaches should be carried out.
- The considered improvement strategy (which may already have its own profitable business model as such or needs the provision of flexibility to have one).
- The cost allocation approach among the aggregator's assets and the revenue sharing model between the MES and the aggregator. As previously discussed, further investigations on these aspects are needed to find the best conditions, for both the MES and the aggregator.

More generally, further studies should be carried out on the identifications and characterization of the different conditions and factors impacting the business models.

It should be reminded that in the base case scenarios, the MES operation is already optimized with respect to the participation in the DA energy market, and this turned out to be the most favorable option for some of the considered case studies. It would be worth to quantify the benefits of this participation to the DA markets for all the case studies. This would need to first consider the current situation of the case studies without the optimization with respect to the DA market (with the actual costs and revenues of the MES, which was not possible in the MAGNITUDE project due to the confidentiality of these data), to compare with the scenarios with DA optimization and to assess the corresponding busines models.

Finally, investigations are also needed on further innovative business models to enhance the integration of different energy sectors.

7 Role models, multi-energy data hub and interoperability layer

This chapter is divided in two parts:

- The first part, Section 7.1, describes the outcomes and lessons learnt from the work carried out on the characterisation of the main stakeholders involved in the electricity, gas, and heating/cooling sectors, in terms of their roles and their main interactions.
- The second part, Section 7.2, is devoted to the specification and implementation of the MAGNITUDE multi-energy data hub and interoperability layer.

7.1 Roles models: the stakeholders, their roles, and interactions

7.1.1 Analysis of the stakeholders

A detailed analysis of the main stakeholders involved in the three considered energy sectors (electricity, gas, heating/cooling) was carried out on the basis of the existing situations in the seven case studies and they were characterized in terms of their roles and their interactions. The results are described in detail in Deliverable D2.1 [1].

The first step was to identify the main essential functions that have to be carried out in each of the three sectors independently of their specific implementation in the different countries. These functions are listed in Table 10 and are mainly of two types: (i) essential functions specific to the considered energy carrier, (ii) non-specific essential functions, even if they involve some specificities of implementation for the different energy carriers.

Table 10 – Main essential functions of the three energy systems

	Energy system		
	Electricity	**Heating/cooling**	**Gas**
Functions specific to energy carrier	Consume electricity	Consume heat/cooling	Consume gas
	Generate electricity	Generate heat/cooling	“Generate/inject” gas
	Deliver electricity (transmission, distribution) • Control the voltage • Manage the congestions	Deliver heat/cooling (mainly distribution, sometimes transmission) • Control the temperature • Control the flow	Deliver gas (transmission, distribution) • Control the pressure • Control the flow
	Balance generation and consumption of electricity • Control the frequency	Balance generation & consumption of heat/cooling • Control the pressure/flow rate	Balance generation & consumption of gas • Control the pressure/flow rate
	Restore the electricity network	Restore the heat/cooling network	Restore the gas network
Non-specific functions	• Measure and check • Coordinate and enable the different processes implied by the carrying out of the energy carrier specific functions		

It appears that the main essential functions in all three sectors are very similar, when taking into account appropriate adaptations. These adaptations result from the rather different characteristics of the electricity, gas, and heat/cooling networks for instance in terms of time constants, inherent resilience, and dynamic behaviours, and therefore from the associated operation needs and requirements which also differ considerably.

These functional similarities led to the identification of very similar roles in the three sectors such as:

- consumers, producers, storage providers of electricity, gas, heat, or cooling,
- distribution and transmission networks operators: in the heating/cooling sector there are mainly distribution networks, but transmission networks can sometimes be found like in the Copenhagen area in Denmark,
- suppliers of electricity, gas, heat, or cooling,
- balance responsible role: the balancing requirement between generation and consumption exist in all three sectors, even the corresponding function is not necessarily carried out by the same type of stakeholders and does not necessarily imply the same types of activities. For instance, in the heat/cooling sector the associated activities are carried out by the network operator and there are no such roles as Balance Responsible Party (BRP) and Imbalance Settlement Agent that can be found the electricity and gas sectors [1],
- metering-related roles and settlement roles,
- regulators, etc.

Other roles found in the electricity and gas sectors do not appear in the heat sector. Indeed, as already mentioned in Chapter 4, there is no market as such in the heat sector and the following roles are currently not found: market operator, broker, trader, or even aggregator, even if they might emerge to some extend in the near future.

Finally, a new role, namely the role of Multi-Energy System operator (or MES operator), was introduced to take into account the cross-sector operation and optimisation carried out in the MESs studied in the project. The assets operated may be consumption, generation, or storage assets, or, depending on the situation, even network assets in the case of the heat/cooling networks.

In a second step, using the integrated and coherent set of roles defined in the first step, a detailed analysis was carried out for the 4 energy sectors (electricity, gas, heating and cooling) for each of the 7 real-life case studies in the current situation, regarding:

- the main stakeholders involved in the case study,
- the roles they carry out,
- the main interactions between these roles.

For each energy sector, the following results were produced [1]:

- A mapping of the actual stakeholders involved in the case study with the roles they carry out.
- Sequence diagrams presenting the sequences of the main interactions between the roles involved and structured according to the three main phases of the service provision process introduced in Section 4.3, namely:
    1. **Procurement and negotiation**: corresponding to the planning and product procurement phase.
    2. **Technical delivery**: corresponding to the product delivery phase.
    3. **Settlement**: corresponding to the settlement or post-delivery phase.

A comparative analysis of the resulting role models (i.e. the roles involved and their main interactions) of the case studies was then conducted for the four energy sectors. This analysis enabled to highlight the similarities between the case studies and to propose generic role models able to represent their main characteristics as described below. As an example, Table 11 compares the roles identified for the electricity sector in the 7 case studies.

Table 11 – Roles identified for the electricity sector in the case studies [1]

Role	Mälarenergi	Paper Mill	HOFOR	ACS	NPT	EMUASA	Paris Saclay
Consumer	X	X	X	X	X	X	X
Producer	X	X		X	X	X	
Storage provider							
MES operator	X	X	X	X	X	X	X
TSO	X	X	X	X	X	X	X
DSO	X	X	X	X	X	X	X
Market operator: • Energy market operator • Balancing market operator	X	X X	X	X	X X	X	X
Clearing & Settlement Responsible							
Broker							
Imbalance Settlement Agent	X	X	X	X	X	X	X
BRP	X	X	X	X	X	X	X
Supplier	X	X	X	X	X	X	X
Aggregator		X		X	X		
Trader	X						
Metering-related roles	X	X	X	X	X	X	X
ICT-related roles: • Data hub operator			X				
Regulator	X	X	X	X	X	X	X

7.1.2 Conceptual technical and commercial functional architectures

MAGNITUDE conceptual technical and commercial architectures were then formalized in the form of generic sequence diagrams, describing the organisation of the stakeholders and the flexibility provision mechanisms. Such generic sequence diagrams were developed for the four energy sectors, namely electricity, gas, heating and cooling sectors.

The generic sequence diagram for the electricity sector was extended to integrate the interactions between the multi-energy systems and the aggregation platform as proposed in MAGNITUDE for the provision of services to the electricity system. It is shown in Figure 41 and described in detail in Deliverable D2.1 [1].

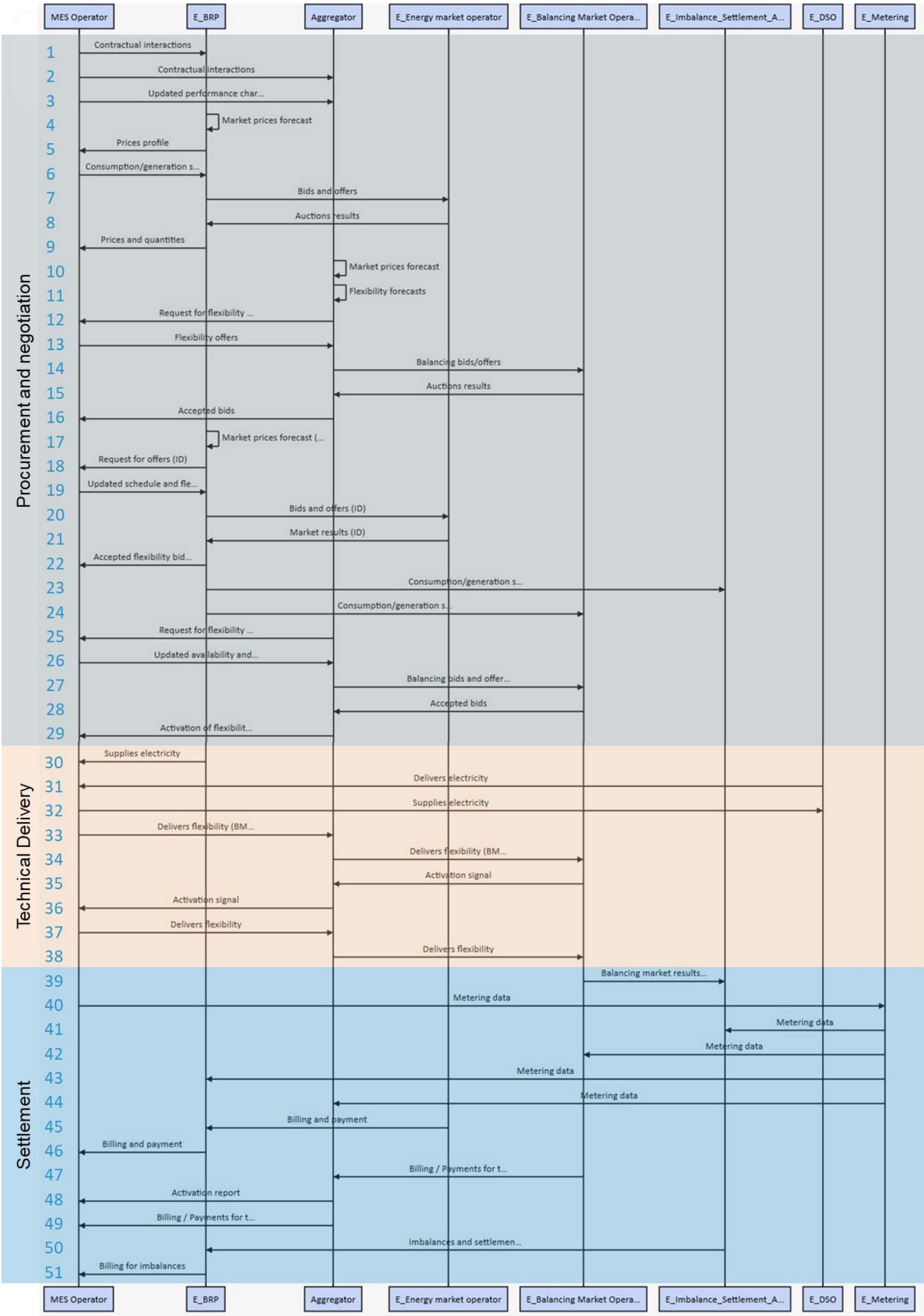


Figure 41 – Generic sequence diagram for the electricity system integrating the interactions between the MES operator and the aggregator

The objective of these developed sequence diagrams is to show the main principles of the whole process and to be as generic as possible. But the whole process may be much more complex when integrating all the specificities that can be found in the considered countries. Indeed, the detailed studies performed in in the project have shown that there is a large diversity of situations, market mechanisms and rules that can be found in the case study countries, despite harmonisation initiatives that have been and/or are being carried out (see Section 4.3). It is not possible to represent all the situations in detail with the same role model. Additionally, as already mentioned, this is a very fast evolving field: some rules or mechanisms can change from one year to the other, or sometimes even faster.

Finally, the roles involved in the two innovative multi-carrier market designs described in Section 4.4 were also identified, and the associated sequence diagrams were elaborated.

7.1.3 Main lessons learnt and recommendations

The similarities between the roles involved in the electricity, gas, and heat/cooling systems show real opportunities in the enhancement of the synergies between the three sectors and their exploitation for the provision of services.

However, the respective operational characteristics of the electricity, gas and heat systems are rather different in terms of time constants, inherent resilience, and dynamic behaviours, and therefore the associated operation needs and requirements also differ considerably. Additionally, as shown in Deliverable D3.1 [2] and previously discussed in Chapter 4, the characteristics of the gas and electricity markets are rather different, both in terms of mechanisms and of time cycles (e.g. trading times, gate closures). In the heat/cooling sector, there is no unbundling contrary to the electricity and gas sectors and for instance network roles may be carried out by producers or suppliers. There are generally no "organized markets" as such, even though, some sorts of "heat market" mechanisms can sometimes be found involving a day ahead planning and intraday adjustments between the heat producers and the operator of the mechanism (for instance in the Greater Copenhagen Area in Denmark [2]). Additionally, heat networks are inherently local systems.

The analyses show that the provision of services by multi-energy systems involves a large diversity of stakeholders in the three energy sectors with deeply different professional cultures, which may bring several types of barriers, such as:

- complexity and multiplicity of interactions/transactions between the stakeholders both inside an energy sector and between energy sectors.
- Additional complexity of business processes and contractual aspects.
- And, beyond industrial, technological and regulatory aspects, a cultural heterogeneity of a more profound nature, since each energy sector has developed its own industrial philosophy to invest, plan, develop, maintain, operate, and remunerate.

Increasing synergies between the three sectors will require evolutions, which will depend on the willingness of the stakeholders, their awareness of the stakes and the potential benefits they can make. There is a need for coordinated initiatives or programs for awareness raising, learning, and training, and to build links between actors in the different sectors:

- First, a clear definition and characterization of the stakeholders' roles and interactions are needed.
- In the short-term, at the local scale, the development of adapted in–situ training program for participants in MES project could be envisaged.

- On the national level, as a starting point, knowledge sharing, and networking events could offer a viable and low-cost solution to begin the process of breaking down institutional silos.
- On the longer term, future engineers and technicians should be educated on the merits of and need for cross-sector cooperation to evolve towards a more collaborative, open working culture and make converge the very different industrial visions in the three energy sectors.

7.2 Multi-energy data hub and interoperability layer

7.2.1 Specifications of the multi-energy data hub and interoperability layer

In the evolving energy systems, the exchange of information is becoming an increasingly complex and resource intense process with many stages, where a growing number of stakeholders is involved.

For example, some ancillary services that, so far, have had long auction periods and product durations (even one week), will have shorter product periods and gate closure times, in accordance to the EU Electricity Market Directive and Regulation [51], [52]. The trading process itself will also become automated and machine-to-machine solutions will replace manual bid submissions in the mid-term. It is, therefore, expected that traders and aggregators will need automatic systems for trading, activation as well as for accounting/payment of customers. This will require the management of an increasing number of connections between pairs of stakeholders and of a significant amount of data. From the IT point of view, exchanges between pairs of actors often take place on point-to-point connections (see Figure 42), creating a so called "spaghetti architecture", which is not scalable and is expensive to maintain in the long run. The absence of standardized procedures for the information exchanges and the spread of spaghetti architectures is reflected in a slowdown in the information exchange and in the fragmentation of information into systems belonging to various companies.

These issues can be addressed through the adoption of a centralised information exchange model and standardised data formats. A data hub, centralised computing architecture (see Figure 42), can provide powerful data integration strategies and improve data management and exchange processes between the different parties connected to the energy systems and markets, providing greater and more consistent data quality and transparency.

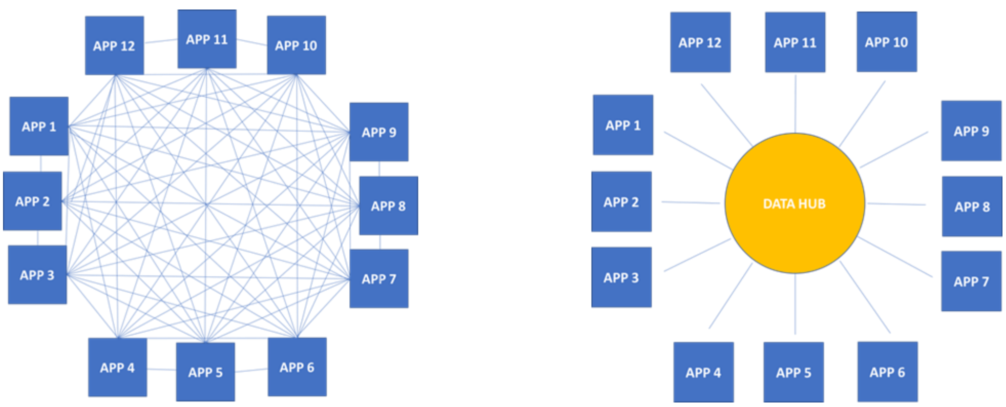


Figure 42 – Point-to-point architecture vs hub-and-spoke (data bub) architecture

Several studies and reports have dealt with the development of data hubs in the electricity and gas sectors, mainly from a retail market perspective, and a centralised approach based on data hubs has already been adopted in some European countries for those energy sectors. In the MAGNITUDE project, the objective is to extend what was already done for the electricity and gas sectors to the heat and cooling sectors by proposing a centralised data hub as a multi-carrier market facilitator, capable of shortening information exchange processes between multi-energy systems (MES), as flexibility service providers, on one side, and commercial and technical stakeholders on the other side, also providing the necessary level of interoperability for the involved stakeholders. The MAGNITUDE solution allows to centralise the information, to persist the data in a queryable data store, to enable the communication for the data sender with a unique system that will take care of delivering the data to the recipient in the most appropriate way. The amount and granularity of data stored in the data hub also pave the way to new sector and cross sectors commercial services, such as personalised offers, demand response, energy audits, home management programmes, smart advices, etc.

The approach adopted in the project has started with a further analysis of the outcomes reported in Section 7.1 [1] above, which has confirmed the great number of interactions between the MES and the other stakeholders, different in each case study and often not automated. In most cases, scheduling data, metering data, and forecasts are exchanged via email on the Internet, in csv or xls formats generally, while contracts and invoices in pdf or text format. In other cases, data are exchanged using proprietary network (such as narrowband PRIME network) and proprietary protocols.

Moreover, as explained in Section 7.1, in the three energy sectors, very similar roles have been identified and the main essential functions appear to be very similar, when taking into account appropriate adaptations for the different characteristics of the different types of networks. Therefore, it is possible to think to adopt the concept of a centralised data hub and an interoperability layer in all these energy sectors, benefitting from the controlled access to domain data for new market opportunities and new energy services inside each energy sector or cross sectors, especially for those actors that operate in multiple energy sectors.

Starting from the analysis of the stakeholders reported in Section 7.1 [1], and mainly focussing on the interactions directly involving the multi-energy systems, a survey has been circulated to collect additional information on the MAGNITUDE case studies, e.g., formats of the data exchanged, data models, eventual standard used, eventual protocol used, frequency of data exchange, etc.

The information collected have brought out potential features and functionalities MES operators, aggregators, and other stakeholders could expect from a software solution that should improve interoperability. This has been formalised in terms of functional requirements. Non-functional requirements, which specify how the system should perform a certain function, constraints, restrictions, security aspects as well as the privacy protection have been identified as well [3].

All the possible ways the user and the system could interact to achieve the user goals have been captured in Use Cases and formalised in Use Case specifications, providing a textual description of the functionality of the system to reach a specific user goal and specifying how the user interacts with a system and how the system responds to the user actions.

High level architecture specifications of the data hub and interoperability framework have been provided by adopting the "4+1 Architecture View Model", which standardizes the software design documents, making the design easy to understand by all stakeholders through multiple views, each describing the system from the perspective of different stakeholders, like end-users, developers, project managers, and testers [3]. The views provided are:

- the **logical view or conceptual view**, which shows the functional requirements related to the final user,
- the **process view**, which describes the concurrent processes within the system,
- the **physical view**, which describes the mapping of software onto hardware and includes some non-functional requirements, such as availability and performance,
- the **development view**, which describes the static organization of the software in its development environment.

7.2.2 Implementation of the multi-energy data hub and interoperability layer

After a thorough analysis of the MAGNITUDE data hub and interoperability layer requirements and high-level architecture described above in Section 7.2 [3], and of possible open-source solutions, the modular open-source FIWARE framework [53] has been adopted as interoperability framework between multi-energy systems and the relevant stakeholders for a secure, efficient, and reliable energy services provision, while the open-source Comprehensive Knowledge Archive Network (CKAN) data management system has been selected for powering the MAGNITUDE data hub and data portal.

FIWARE is a curated framework of open-source platform components that can be assembled together and with other third-party platform components to accelerate the development of smart solutions. FIWARE was born in Europe from the Future Internet Public Private Partnership (FI-PPP) [54], with the aim of:

- accelerating the development and adoption of future internet technologies in Europe,
- advancing the European market for smart infrastructures, and
- increasing the effectiveness of business processes through the Internet.

FIWARE allows to publish, consume, and subscribe to data coming from multiple sources. The FIWARE ecosystem is composed of a number of modules and services, called Generic Enablers (GE). Not all the GEs must be implemented inside any custom "powered by FIWARE" application giving the modular nature of the framework. The following GE have been selected for the MAGNITUDE interoperability framework goals:

- Orion Context Broker: it is the core component of the FIWARE framework. It allows to publish, consume, and subscribe to data coming from multiple sources. It also owns a data store, using an instance of MongoDB as its internal data store, where data in the short to medium term are persisted.
- KEYROCK Identity Manager: it manages permissions and policies to resources allowing different access levels for the users. KEYROCK operates in conjunction with the other security components, namely WILMA PEP GE, responsible for enforcing access control to protects the resources, and AUTHZFORCE PDP GE, responsible for OAuth2-based access determination based on the policies defined.
- Cygnus connector: it allows to store data in the long term into the MAGNITUDE data hub.

Beside the modularity, another interesting aspect of FIWARE is the fact that it is based on Next Generation Service Interface (NGSI), which is a protocol developed by the Open Mobile Alliance to manage Context Information related to a Context Entity (e.g., a room). NGSI RESTful Application Programming Interface (API) via HTTP allows clients to:

- query context information,

- update context information,
- get notified when changes on context information occur,
- register context provider applications.

The FIWARE NGSI API defines:

- a data model for context information, based on a simple information model using the notion of context entities,
- a context data interface for exchanging information by means of query, subscription, and update operations,
- a context availability (interface for exchanging information on how to obtain context information).

A wide range of NGSI IoT Agents GE are available in the FIWARE ecosystem for interfacing easily with devices using the most widely used IoT protocols (LWM2M over CoaP, JSON or UltraLight over HTTP/MQTT, OPC-UA, Sigfox or LoRaWAN): FIWARE NGSI Agents allow to simplify the management and the integration of devices by collecting data from devices through heterogeneous protocols and translating them into the standard NGSI platform language. Guidelines are provided to implement NGSI to interface with other systems. This opportunity has been exploited in the project [55] to implement a custom NGSI Agent to enable through the FIWARE framework the interactions between a MES and the aggregator as defined in MAGNITUDE [10] using the OpenADR protocol. OpenADR 2.0b is an open and interoperable information exchange model (a full IEC standard, known as IEC 62746-10-1 ED) that standardises the message format used for automated Demand Response (DR) and Distributed Energy Resource (DER). MAGNITUDE exploits the opportunity to extend the semantic of OpenADR, provided by for the standard itself, to propose OpenADR as a protocol to convey the information exchanges between the MES and the aggregator. It can easily be proved that also the information exchanged between the MES and its stakeholders can be conveyed via OpenADR as well.

While real-time information is exchanged through FIWARE context Broker, the CKAN based data hub of the MAGNITUDE project has been conceived to store and index asynchronous data so far exchanged in the three energy sectors as files attached to emails, thus using a peer-to-peer approach. The MAGNITUDE multi-energy data hub and data portal are able to shorten information exchange processes in general. CKAN is a solution for the publication, management and consumption of open data, usually, but not only, through static datasets: it allows to catalogue, upload and manage open datasets and data sources, and supports searching, browsing, visualizing or accessing open data. It also offers a powerful API that allows third-party applications and services to be built around it. The CKAN software can be customised with ‘extensions’, which are a simple way to extend core CKAN functions according own requirements, without interfering with the basic CKAN system. The MAGNITUDE CKAN based data hub has been enriched with a Postgres database and with the following extensions:

- CKAN DataStore: it provides an ad hoc database for storage of structured data from CKAN resources. Data can be pulled out of resource files and stored in the DataStore.
- DataPusher: it allows to automatically download any tabular data files like CSV or Excel from a CKAN site's resources when they are added to the CKAN site, parses them to pull out the actual data, then uses the DataStore API to push the data into the CKAN site DataStore.

Figure 43 shows the final MAGNITUDE data hub and interoperability layer architecture [55].

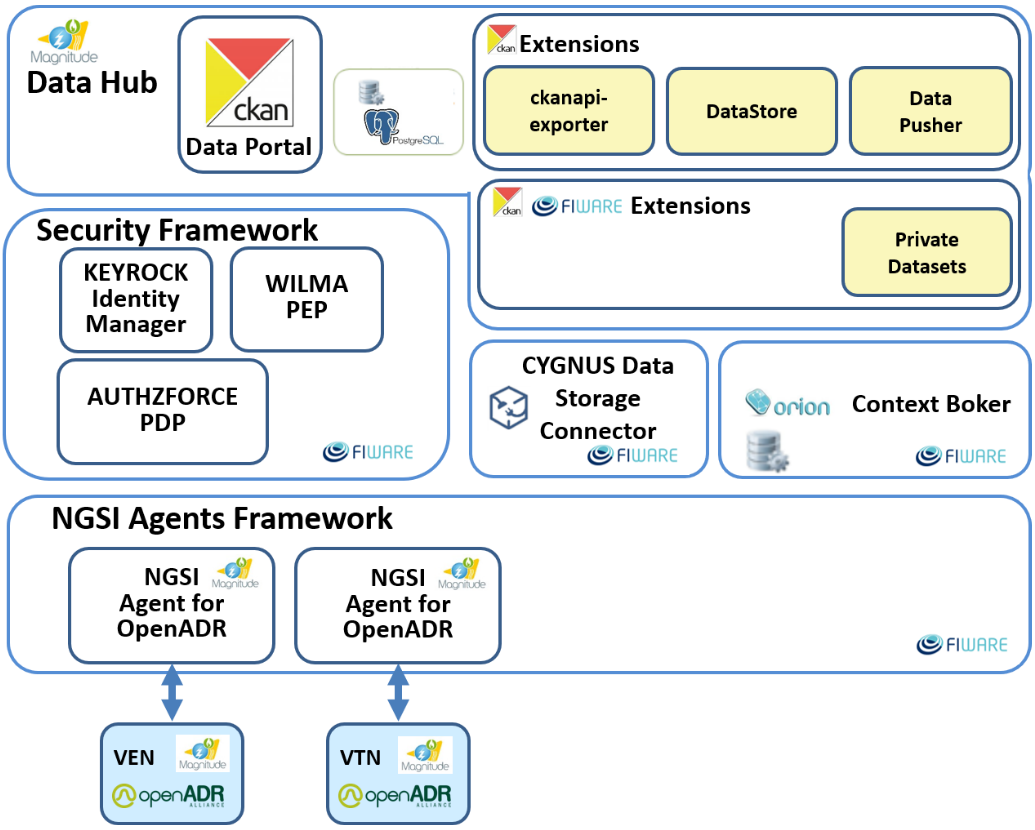


Figure 43 – MAGNITUDE data hub and interoperability layer architecture

7.2.3 Main lessons learnt and recommendations

A multi-energy data hub and interoperability layer can provide significant benefits:

- A centralised information exchange system and standardized procedures allow to speed up interactions thus improving operational and business services. Additionally, the reduced number of interfaces in the hub architecture decreases implementation costs and increases operational efficiencies.
- The amount and granularity of data in a data hub could pave the way to new operational and business opportunities, for instance:
  - Customers, who consume energy in various forms, could manage the contracts with their suppliers in a simpler and more immediate way, or they could (consequently) switch more easily between suppliers, thus achieving significant savings in utility bills (especially considering that retailers are often multi-utilities that sell energy on multiple carriers). Furthermore, they could access, in a single point, the history of their consumption of different forms of energy, gaining greater awareness of their energy usage.
  - Retailers, often multi-utilities, could have access to consumption and production on the various markets in one place, managing to size up affiliate campaigns based on the customer's energy mix.
  - DSOs and TSOs could have information from producers, resellers, aggregators, consumers, all available in one place. This information would be useful for balancing the energy distribution and transmission networks and would facilitate the activities of multiple networks distribution and transmission operators.

- A new generation of aggregators could emerge operating not only in the electricity sector but also in other energy sectors.
- MESs could have a single point to exchange information with stakeholders from all the energy sectors and could access data to use their own conversion technologies to produce energy in the form most requested and best paid by consumers by transforming energy from the form less requested and therefore less paid, maximizing their profits.
- New players could be authorised by the customers to access metering data and smart devices to develop new services to increase energy awareness and to improve energy efficiency through smart advices.

Furthermore, the open-source movement encompasses a wide collection of ideas, knowledge, techniques, and solutions that is worth exploring and reusing whenever possible.

The use of FIWARE technologies has a multidimensional impact on MAGNITUDE, since they not only provide a technological framework, but a community of corporates, startups and experts working together to deliver cutting-edge technological solutions to the global markets, offering a stable framework that ensures the high quality and sustainability of the services through it.

Moreover, by being a member of the FIWARE ecosystem gain the opportunity to raise visibility and achieve high credibility, as part of a global force of innovation key-players that aim to create solutions of tomorrow.

However, some barriers have also been identified, such as the tendency to avoid modifications of consolidated processes, or the lack of confidence in technological innovation, which could limit the adoption of the proposed solution.

8 Recommendations for further research, development work and projects

Based on the main outcomes and lessons learnt from the project, this chapter is devoted to the description of the remaining challenges and the recommendations for future research and development work, as well as recommendations for future demonstration projects.

Since some of the recommendations that were presented in the previous chapters already concerned future work, there will be some unavoidable repetitions with respect to what was already written in this report.

8.1 Remaining challenges, recommendations for future research and development work

In the project, the optimisation and coordination tools and algorithms were developed with the aim of achieving stable prototypes with Technology Readiness Level (TRL) 3, 4 or even 5 for some of them. Further research and development work are therefore required to bring them to higher TRL. This concerns in particular:

- The aggregation platform software tools and modules.
- The MES simulation and optimization models and tools.
- The multi-energy data hub and interoperability layers.
- The multi-energy market simulator.

Further investigations are also needed on the following topics:

- Flexibility capabilities of MES and cross-sector technologies.
- Services that can be provided by MES.
- Trading of MES flexibility, regulation, and services procurement mechanisms.
- Innovative market designs.
- Business models assessment for MES operator and aggregator.
- Coordinated planning and operation of energy networks.
- Future energy system.

Aggregation platform software tools and modules

Additional functionalities need to be developed to better support the requirements of aggregators and energy traders. In this respect, it is necessary to approach utilities and aggregators to present the developments of the aggregation platform and get feedback about additional functionalities required to become ready-to-market (TRL8).

In particular, the aggregation platform modules need to get adapted to national requirements of the electricity and ancillary service markets in order to implement automatic trading as a means to deal with the upcoming changes. For instance, frequency ancillary service markets undergo a reorganisation because of the go live of MARI and PICASSO initiatives.

On the functional level, improved forecasting of the market prices and MES flexibility is needed, and further research and development work should be carried out on these topics. For instance, the simplified modelling of large MES for flexibility forecasting, and the description and forecasting of the swarm behaviour of a large number of small MES (e.g. heat pumps, HVAC, electric boilers) in the aggregation platform are further objectives for short-term development.

MES simulation and optimisation models and tools.

The tools developed in the project for the simulation and optimization of MESs were essentially devoted to support their operational planning, namely the (optimal) schedule of the technologies involved in the MESs in order to better face the energy demand of the process and the purchase/sales of the resources needed to supply the MES or generated by the MES.

The simulation and optimisation tools now need to be further developed and engineered to be able to support the daily work of MES plant operators, which means to develop suitable functionalities to completely cover the planning and the operation of the plants in order to optimize their management and better exploit their potentiality especially in terms of flexibility provision.

One aspect of the remaining work to be done will consist in developing the tools to operate the plant once the daily plan has been set/accepted, integrating the service provision on the markets. The tools will have to support the "implementation" of the plan set during the operational planning stage and take care of the load/demand following functionality during the daily/weekly operation. The tool will also have to manage the provision of market services, as planned at the operational planning stage, and required by the system operator through suitable activation signals. A one-minute (or finer) time resolution is needed to reliably face the control variables of the plant and to ensure the satisfaction of the real demand and the reliability of the operation. For instance, with a one-minute time resolution, it will also be possible to properly implement the provision of mFRR market service. However, for the activation of FCR and aFRR, which are faster services, it will be necessary to adopt a finer time resolution.

As shown in Chapter 2, storage devices are key technologies to increase the flexibility that can be provided by MES. But further investigations are needed on strategies to better exploit storage devices for flexibility provision. Indeed, the simulations showed that, at the operational planning stage, these devices were exploited in a reliable way to support the MES energy demand, but with some limitation for the market service provision. This is due to the stochastic nature of the ancillary service activation, which can lead to unfeasible storage management, e.g. when the storage is scheduled to support a market service provision and that the market service is not activated, the storage operating program may in some cases become unfeasible.

From the above two paragraphs, it appears that an important challenge is the appropriate integration of the tools for the operational planning and operation phases of the MES, taking into account the actual capabilities of the resources (technologies, demand, markets, storage) to optimise the flexibility that can be provided.

Another aspect is the modelling of carrier networks, which is relevant both at the operational planning and the operation stages. It would be necessary to further detail and develop the models to take into the account the whole complexity of the MES. Indeed, the analysis carried out in the project used simplified models of the multi-carrier networks, exploiting the available operating data. These models didn't affect the reliability of the project outcomes. However, in view of future real-life implementations of the tools, the optimization process should include a detailed model of the behaviour and operation of the networks, during the energy demand satisfaction and the market service provision. This is a challenging task as real multi-carrier networks are generally very complex in terms of nodes, length, and interactions. For instance, in the case of district heating the heat network can include tens hundred nodes, its length can be several tens of kilometres and it can be connected by tens of nodes to the electric network (this is the case of district heating system with a distributed architecture). Besides that, few examples can be found in most recent scientific papers.

Multi-energy data hub and interoperability framework

The data interoperability among stakeholders working in energy networks is a key research topic.

In the short and medium term, the multi-energy data hub and interoperability framework developed in the MAGNITUDE project should be further extended and developed, to provide a solution to facilitate the interactions and ensure the interoperability among all the stakeholders of a multi-energy context.

For instance, a new NGSI agent based on OpenADR was developed to allow the interaction between the MES and the Aggregation Platform. Many other interactions could be implemented by exploiting the potentialities of the proposed technological solution: this work could be done by the development of new NGSI agents that can convey the information exchanged among other stakeholders.

The analysis of the different MAGNITUDE case studies has proved that many different stakeholders are involved the electricity, gas, and heating/cooling systems and that they exchange information in different formats, through different protocols, in compliance with different constraints. In most cases, information is exchanged via e-mails, phone calls, textual documents sent as e-mail attachments etc. Most of these data exchanges are often not standardized, not automated and in some case are not in place but still in progress. Future research initiatives should spend effort not only in the development of the technology but on convincing stakeholders to adopt standard data formats and communication mechanism.

The main challenge that must be addressed is thus the adoption of automated communication mechanisms in order to improve the interactions among the different actors. Investigation of proper management systems for the stakeholders, that can natively interact, should be carried out with the interoperability layer developed by the project

New business opportunities linked to the development of multi-energy data hub and interoperability layers should also be investigated.

Finally, considering more specifically the aggregation of MES, standardization of the communication between the MES and the aggregation platforms would significantly reduce the costs of integration of new flexibilities into existing aggregation portfolios. Investigation at the European level would be needed and should include common data models, interfaces and protocols, ICT security, and plug-and-play functionalities.

Innovative market designs

Within the MAGNITUDE project, five innovative multi-carrier market schemes were proposed (Figure 33). Two of them were investigated in more detail: a single carrier energy market scheme with separate, sequential day-ahead markets for different energy carriers and a unified multi-carrier energy market scheme with one unique multi-carrier market and market operator. The other market schemes with single and/or multi-carrier markets at local and/or global level were only analysed qualitatively and could thus be a subject of further research.

In the project, we investigated the design of three integrated multi-carrier gas, electricity and heat market models and their mathematical formulation, linked to the unified multi-carrier energy market scheme mentioned above. The integrated multi-carrier market design with centralised clearing, which is expected to be the most effective design in terms of economic efficiency, was implemented in the market simulator and assessed on a case study representing the Italy North region. However, the real-life implementation of this design is challenging due to technical and organisational barriers (for instance, the different market operators should merge into a unique market operator). For this reason, two alternative decentralised multi-carrier market designs were also proposed. The advantage is that, next to largely preserving the organisational market structure, a decentralised market setting preserves the limited exchange of potentially sensitive operational information between market participants and market operators. The organisational impact of these alternative market designs should be further investigated. Additionally, the decentralised multi-carrier market designs rely on decomposition techniques and introduce additional computational complexity and more research is needed on the appropriate decomposition techniques to be used.

More generally, a detailed analysis of organisational aspects, such as changes in roles, responsibilities, and regulation, would be needed in relation to the different proposed market schemes.

In MAGNITUDE, we focused on the merging or close cooperation of market operators of different energy vectors during the day-ahead market clearing. However, there are other possibilities for coordination, (e.g., in terms of information exchange) that should be further explored. Additional research on the forms of market-based integration of energy vectors (e.g. from explicit integration of markets and merging market operators to different coordination forms among the market and system operators) is needed.

Further analysis and simulation of different use cases (in different contexts and regions) would also be needed as within Magnitude the multi-carrier markets were only simulated for one scenario and region, i.e. Italy Nord.

Beyond the conceptual work and case-study-based comparison of the innovative multi-carrier market organisations carried out in the project, the proposed market designs would require more thorough analyses, including Cost Benefit Analyses (CBAs) taking into account the implementation costs and the impact on the transactions costs for all the stakeholders involved before a real-life implementation can be considered.

In MAGNITUDE, we mainly focused on market designs at the global level (national, regional). More research would be needed to explore market designs or business models in the local context (e.g. linked to residential, commercial or industrial multi-energy systems (MES), energy communities, etc.), and for instance, assess the possible added value of the proposed market designs.

There are other topics, which would need further investigations in the form of more fundamental, academic contributions of the work done in MAGNITUDE:

- Continue the work to quantitatively analyse interactions between storage and conversion technologies in an integrated multi-carrier energy market.
- Study the pricing questions related to integration of advanced bidding products with integer constraints in the context of multi-carrier energy markets.
- Investigate optimal bidding behaviour of conversion technologies in more integrated multi-carrier markets.
- Study the impact of imperfect forecasts on market clearing results for different proposed market designs.

Multi-energy market simulator

The developments of the multi-energy market simulation software tool have focused on the implementation of the computational engine required to clear the integrated multi-carrier market design with centralized clearing. This design was quantitatively assessed and compared to the decoupled multi-carrier market design with decentralised clearing, on a case study representing the Italy North region. Further extensions of the market simulator with alternative market designs could also be considered, such as alternative set-ups with multi-carrier markets at local and/or global level.

The market simulator can also be used as a supporting tool in future research tracks. The simulator can be used to analyse different alternative multi-carrier market designs for certain future scenarios and contexts (e.g. geographic area) to provide insights to advise different stakeholders on the impact of changes to the market design such as national and European policy and decision makers.

Alternatively, the tool can be used to assess the impact of the introduction of new technology in an existing system on the market outcomes and to calculate revenues of this new technology on the day-ahead markets.

Finally, the multi-carrier market simulator currently does not include any network models. With the upcoming electrification of heat and mobility sectors, network constraints, particularly at the local level, will become increasingly important. A relevant extension of the market simulator is therefore to incorporate a representation of at least electricity networks, and preferably network dynamics of all considered energy vectors.

Business models

As already mentioned in Chapter 6, further research are needed on the identification and assessment of the conditions and factors, which impact the profitability of MES business models:

- the regulatory framework, market rules, and mechanisms for the procurement of flexibility, e.g. the remuneration structure of the services, the grid tariffs, the energy prices and taxes, etc. Evolutions/improvements of the market design and regulatory framework (e.g. see Section 4.3.2) should be investigated, along with their impact on the exploitation of the flexibility that MES can offer in the future electricity system with more renewables.
- Alternatives approaches for the operation and optimization strategy of MES to provide flexibility.
- The cost allocation approach among the aggregator’s assets in the pool, as well as the revenue sharing model between the MES and the aggregator in order to find the best conditions, for both the MES and the aggregator.

In the project, in the base case scenarios, the MES operation was already optimized with respect to the participation in the DA energy market, and this turned out to be the most favorable option for some of the case studies. It would be worth to quantify the benefits of this participation to the DA markets for all the case studies.

Finally, investigations are also needed on further innovative business models to enhance the integration of different energy sectors.

Technologies and flexibility potentials

As mentioned in the previous Chapters, further investigations should be carried out on the technologies and their capability to provide flexibility, for instance:

- Storage technologies (e.g. at high temperature levels) and their integration both at large and small scales, in particular in district heating networks.
- Conversion technologies (e.g., high temperature as well as large-scale heat pumps).
- Low temperature heat networks.

- Improved control strategies and ICTs for a better integration of each technology.
- The best practices and best combinations of technologies and fuels to both meet the requirements of the MES and provide flexibility.
- Improved design of conversion technologies (Power to X – P2X – and X to Power)
    - design for operational flexibility – changes on set points, dynamic performance, and intermediate storage in complex plants.
    - design for broad range of operation, e.g. efficiency and lifetime.
- In the same way, improved design, planning and operation of MES plants for integration in a RES dominated energy system

Further research is also needed on the quantification of the flexibility potential of MES.

Services for distributions networks and DSOs

In MAGNITUDE, service provision for congestion management on the distribution network was studied in only one case study. More detail investigations are required on flexibility utilization to support the operation, development, and planning of distribution grids in order to assess the potential benefits and raise awareness about cost saving potentials.

Coordinated planning and operation of energy networks

Research work is needed on the coordinated planning and operation of different energy networks/infrastructures, as well as the development of tools that combine short-term operational features and long-term system planning integrating flexible resources. This means analysis tools that:

- ensure that operational constraints are realistically represented in system planning tools,
- system network infrastructure planning includes operational issues and network limitations, as well as mitigation actions from the use of flexibility.

This also includes optimized exchange of services between energy carriers.

There is also a need for detailed analyses and quantification of potential benefits and costs of such coordinated planning and operation of energy networks.

Future energy system

In the context of the evolution of energy system, research work would be necessary on the following topics:

- Long-term energy system and stakeholder investment models for system expansion and decision support, that include networks, cross sector flexibility and market interactions.
- Assessment on the MES flexibility provision of the ongoing and future regulatory evolutions, such as
    - Ongoing harmonisation of the European flexibility markets. As already mentioned, several European harmonisation initiatives are currently ongoing on flexibility market designs. The tendency is heading closer to real-time operation, resulting in market design changes such as finer product time resolution, shorter imbalance settlement periods and reduced gate closure times.
    - Ongoing process to transpose the EC Clean Energy Package for all Europeans into national laws, including for instance the new status of Citizens Energy Communities and Renewable Energy Communities,
    - Increased coordination between the energy sectors at the global and local levels, reform of taxes and levies in link with decarbonation, and not anymore with the type of energy, etc.

  - New rounds of European legislative debates from mid-2021 to support the European Green Deal adopted in December 2019.
- Evolutions of the sectoral regulatory framework that might be needed to monitor and control the development of innovative multi-carrier markets, in particular at the local level.
- Potential longer-term evolution of energy markets and regulatory framework.
- Finally, on a larger perspective, studies are also needed on the societal aspects of energy sector integration, for instance acceptability of MES projects or awareness raising of potential benefits, that could lead for instance to the design of new approaches for local concertation, local financing, etc.

8.2 Demonstration projects

Demonstrations projects would allow to assess the tools developed in MAGNITUDE in real-life conditions and will support their development to higher TRL. More specifically,

- This would allow to validate the **multi-energy aggregation platform software tools** in a real multi-utility (electricity, gas, heat) environment and to test additional functionalities developed to better support the requirements of aggregators and energy traders. Such demonstration would require the adaptation to the national market APIs and trading procedures.
  Additionally, due to their role as critical infrastructure, the energy supply industry and in particular electricity transmission and distribution is very reluctant to operate any software tools in a cloud environment. The implementation of aggregation platforms in storage clouds like GAIA-X should be demonstrated in order to reduce the concerns of the electricity industries about data security, data privacy and performance of storage clouds.
- The behaviour of the **tools developed in MAGNITUDE for the operational planning and operation control of the multi-energy systems** could be practically experimented on MES in real conditions, which will give precious feedbacks for further development and the benefits arising from their adoption could be fully assessed. In this respect, the participation to demonstration projects in Horizon Europe research program will be a good opportunity.
  The **validation of the models** is another critical point, which is generally due to the lack of enough real-time monitoring equipment in the multi-carrier networks and could be an important aspect of a future a demonstration project.
- The validation of the **multi-energy data hub and interoperability layer** could not be considered in MAGNITUDE because the project had no real-life pilot where to test the developed software. So, in a demonstration project, the real-life validation could help to further refine the developed software and assess its potential benefits.
- **The multi-energy market simulator** can be used and further developed in demonstration projects to assess different multi-carrier market designs for future scenarios and different contexts. As previously mentioned, it can also be used to analyse the impact of the introduction of a new technology in an existing system on the market outcomes.

Other topics for demonstration projects have also been identified, based on the research and development work described in the previous section, for instance:

- Pilot projects to implement and study new market designs or business models in the context of local multi-carrier systems.
- Study and test concepts for an enhanced coordination between energy markets.

- Regulatory sandboxes to implement and test innovative multi-carrier market concepts, flexibility procurement mechanisms and market-based energy sector integration in real-life.
- Demonstration of the economic viability of flexibility provision in accordance with system needs, and test and characterisation of the profitability conditions of the business models for energy system participants: MES, aggregator, etc.
- Exploitation of MES flexibility and provision of services to support the operation and development of distribution grids.
- Implementation of concepts and demonstration of coordinated planning and operation of different energy networks/infrastructures integrating flexible resources and with exchange of services between energy carriers.

These topics have been described in Section 8.1, and will not be further detailed here.

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