D1.2

Technology and case studies factsheets

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 774309.

D1.2 – Technology and case studies factsheets

Grant agreement number:	774309	Due date of Deliverable: 31/01/2019
Start date of the project:	1 October 2017	Actual submission date: 03/04/2019
Duration:	42 months	Deliverable approved by the WPL/CO: ☒

Lead Beneficiary: **EIFER (Europaisches Institut für Energieforschung EDF-KIT EWIV)**: Nicole Pini, Karol Witkowski, Stephan Seidelt, Paul Haering

Contributing beneficiaries: **Cardiff University:** Yue Zhou, Meysam Qadrdan

Danmarks Tekniske Universitet: Angelina Syrri, Henrik W. Bindner

Mälardalens Högskola: Hailong Li, Jakub Jurasz

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

Keywords
Sector coupling technologies, flexibility services, power-to-heat, power-to-cold, heat-to-power, gas-to-power, storage, real-life case studies

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

History			
Author	**Date**	**Reason for change**	**Release**
EIFER	29/03/2019	Final version for submission	R1

1 Executive Summary

The present report is a public deliverable (D1.2) of the MAGNITUDE H2020 funded European project. The MAGNITUDE project aims at developing business and market mechanisms, as well as supporting coordination tools to provide flexibility to the European electricity system, by enhancing the synergies between electricity, heating/cooling and gas systems.

Seven real-life case studies of multi-energy systems of different sizes and technological features located in seven European countries are used to provide the data foundation for the assessment and analysis carried out in the frame of the project.

The work presented here is a follow-up of the public deliverable D1.1. This first report aimed at analyzing the current set-up of the case-studies, describing the technologies and control strategies that are currently in place and identifying options for improving the flexibility provision while considering success factors and bottlenecks.

Deliverable D1.2 seeks to gather data from on-going and finished projects, available studies, manufacturers and case studies. These data are required for the simulation, optimization and development activities carried out in other Work Packages (WPs), as well as to evaluate expected developments of each of the identified sector coupling technologies. The main objective is to characterize the flexibility properties of coupling technologies either alone or in a specific configuration, and then to describe their ability to provide the flexibility services benchmarked in Deliverable D3.1.

This information will be further used as an input in other WPs to make forecasts of the technologies' flexibility potential and corresponding costs. Based on the findings of both Deliverables D1.1 and D1.2, Deliverable D1.3 will issue recommendations on how technologies should evolve, in the light of new results obtained in different project WPs, to support the provision of flexibility services through sector coupling technologies and to foster synergies between stakeholders from the electricity, heating/cooling and gas sectors.

Methodology

For data collection purposes, a questionnaire was developed and sent to the case study owners or their contact points. Once all the questionnaires were evaluated, a factsheet template containing a list of Key Characteristics (KC) was designed and completed for each identified sector coupling technology based on literature data and – when available - specific information on the technologies' integration in the case studies. Section 3 of the report presents the perimeter of the analysis and the factsheet template used for the assessment. Workshops organized with the contact points of the case studies allowed to integrate the missing information. The information collected through the questionnaire, the factsheets and the workshops are summarized and commented in Section 4 of the deliverable.

Then in Section 5, the capability of sector coupling technologies to provide flexibility services are evaluated on the basis of the services requirements identified in Deliverable D3.1 and improvements options selected for each case study are described. Finally, current technological bottlenecks limiting the provision of flexibility services and expected developments of technologies are summarized. The main results are presented in the following paragraphs.

Technical suitability to services

Technologies have been characterized and described according to parameters such as power-ranges, start-up times and ramp rates to assess the capability of each of them to provide certain flexibility services. 3 parameters are particularly important when considering flexibility provision:

- Ramp-rate, expressed in units of power over time, which indicates how quickly a power plant's 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 are 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.
- The power range, expressed in units of power. Technologies vary greatly in capacity. The aggregation of several units through the implementation of an appropriate ICT infrastructure allows to reach higher capacities.

When switched off for an extended period, steam turbines and Combined Cycle Gas Turbine (CCGT) require up to several hours to reach back nominal power. To reduce the time needed to react to a grid issue and be able to provide flexibility services within a short period, some units can be held in hot reserve to provide reserve capacity quickly. As shown in the figure below, this allows to decrease the hot start time to values from a few minutes to 45 minutes for CCGT plants (orange) and 2 hours for steam turbines (green).

Simple cycle aero-derivative turbines (large dark brow circle) and electric boilers (purple) are characterized by a high ramp rate and a short start-up time. These two features make them particularly suitable for the provision of frequency containment reserve. Heat pumps (dark blue) and Organic Rankine Cycle (ORC) turbines (red) – two technologies with a low maximum power output – require to be aggregated to offer larger volumes in order to meet market entry conditions. The aggregation of domestic heat pumps for the provision of reserve in power systems has been demonstrated in several pilots.

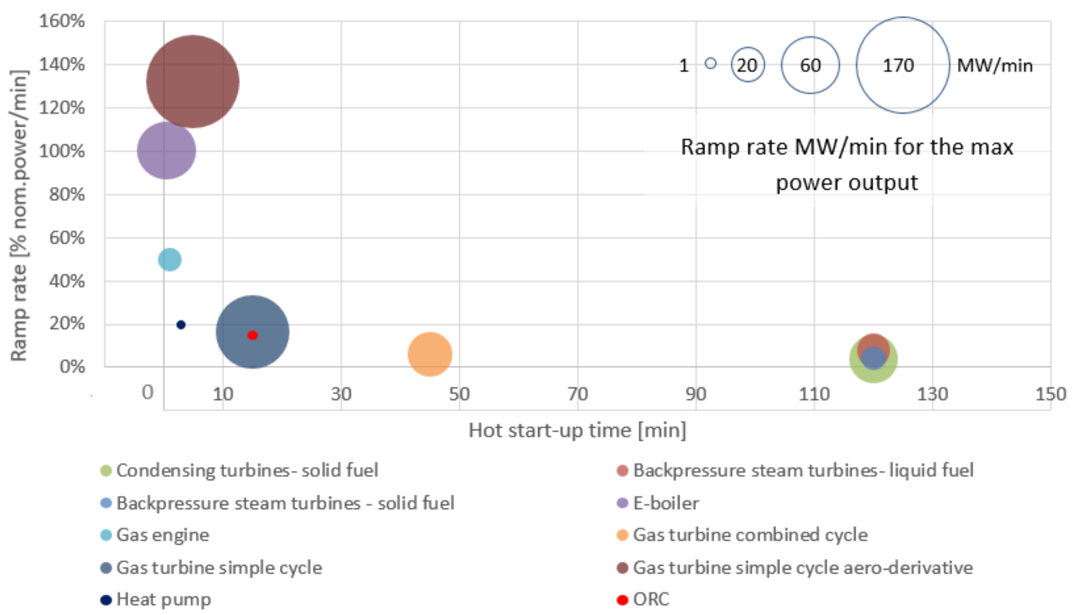

Figure 1: Ramp rates [% nom.power/min] and [MW/min] for the biggest power output in a relation to hot start-up time

To summarize, it appears that coupling technologies with short ramp-up and start-up times and a high power output such as e-boilers, gas engines and aero-derivative turbines meet requirements for frequency containment reserve markets. Gas turbines and aggregated heat pumps/chillers and ORC systems are suited for the participation in the short-term energy balancing markets. Sector coupling technologies with less flexible capabilities such as condensing turbines and steam turbines cannot provide the full range of flexibility services. They seem to be most relevant for intraday and day ahead energy markets. Heat and gas storage can increase the flexibility provision of the above-mentioned technologies or system configurations to which they are coupled or in which they are integrated.

Case study improvement options

The main characteristics and improvements options leading to more flexibility provision or a more efficient use of resources are summarized for each case study in the table below.

Case study	Heat generators	Steam turbines	Gas turbines	Gas turbine - CCGT	Gas engines	Chillers	Heat pumps	Electric boilers	Thermal Energy storage (TES)	Gas storage	Improvement options
Mälarenergi AB - Sweden	X	X				X	X		X		- Integration of a thermal storage tank to produce additional electricity - Provision of frequency control by distributed heat pumps when heat demand is high
Paper Mill (productions line 1 & 2) - Austria	X	X							X		- Installation of a new steam accumulator that would reduce steam blow-off, reduce fuel consumed for steam generation and increase the flexibility of the steam turbines - Optimization of the operation of the whole facility by minimizing gas and electricity peaks
	X	X									
Hofor - Denmark	X						X	X	X		- Integration of a control and communication interface that allow aggregation and service provision through heat load shifting in buildings
ACS - Italy	X				X		X	X	X		- Investigation of the different operation modes of the thermal storage - Study of the new pricing models for heat (day/night tariffs) to optimize the heat demand response - Development of predictive model for thermal load forecast - Improvement of electrical network which will allow to provide Frequency Containment Reserve (FCR)
Neath Port Talbot - United Kingdom	X	X	X	X							- Provision of flexibility from gas-fired generators using fuel from high-pressure gas distribution networks
EMUASA - Spain	X				X					X	- Integration of a chiller for the production of cold and of a gas storage to exploit flexibility coming from the gas production line
Paris Saclay - France	X						X				- Integration of heat pumps and thermal storage in building and at substations

Figure 2: Summary of Case Study flexibility improvement options based on the available technologies

The integration of thermal storage is the most widespread improvement solution among all (Mälarenergi, Paper mill, ACS and Paris Saclay). This is due to the fact that all 7 case studies are equipped with heat generators. The provision of flexibility through the aggregation of heat pumps is an option selected for Malärenergi, Hofor and Paris Saclay. EMUASA and Neath Port Talbot will investigate how gas to power and gas storage technologies can provide additional flexibility.

The integration of a chiller for cold production will also be evaluated for EMUASA. Furthermore, studies will be carried out for the Paper mill and ACS to see if other improvement options can be of value.

Major trends and expected developments of the energy system in the European Union (EU)

The energy system and market undergo a transformation driven by a rapid growth of renewables, climate change, decarbonization, digitalization, and the electrification in the heating and cooling and the transport sectors. The major trends and developments identified in the EU Reference Scenario 2016 with projections until 2050 are an increased penetration of Renewable Energy Sources (RES), strong energy efficiency improvements, technology cost reductions, emissions standards for mobility solutions and increasing Emissions Trading System (ETS) prices. The trends for the considered sector coupling technologies are summed up below:

- Power to heat: the steam and heat demand in the EU28 is expected to remain approximately stable throughout the projection period. In the long term e-boilers and heat pumps penetrate the district heating market and increase their market share while solid and gaseous fuels see their share reduced.
- Power to cold: the demand for air conditioning will increase because cooling degree days are assumed to augment. Thus, more chillers will be rolled-out in the residential sector. These small units can be aggregated to collectively address grid issues.
- Gas to power: gas-fired generation slightly increases due to the role that gas is playing as a back-up technology for intermittent renewable sources. The majority of investments are in CCGT plants used for flexibility and reserves. The share of Combined Heat and Power – CHP - (mainly fueled with gas and biomass) will increase following the general trend towards highly efficient power plants.

The EU Reference Scenario does not take into account supporting technologies such as heat and gas storages. However, it can be assumed - based on the improvements options selected for the case studies - that hot water tanks and steam accumulators will play a key role to compensate daily, weekly and seasonal fluctuations in heat demand. Combined with other coupling technologies such as e-boilers, heat storages can provide additional flexibility to the power system and support the integration of renewable energy resources. (Bio-)Gas storages will remain a niche market that will mainly serve to exploit flexibility in industrial sites where gas production or demand is important.

One of the biggest challenges of the energy system transformation will be to coordinate the development of coupling technologies and flexibility markets in Europe. Deliverable D1.3 will develop recommendations on how the technologies and energy systems should evolve to support the deployment of flexibility products and create synergies between the energy sectors.

Table of content

Table of figures

Table of tables

List of Acronyms

Abbreviation / Acronym	Description
AC	Alternating Current
AD	Anaerobic Digestion
aFRR	Automatic Frequency Restoration Reserve
AWHP	Air-Water Heat Pump
CAPEX	Capital expenditures
CCGT	Combined Cycle Gas Turbine
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
COP	Coefficient of Performance
CS	Case Study
DA	Day-ahead
DH/DHS	District Heating System
DHW	Domestic Hot Water
DSM	Demand Side Management
EER	Energy Efficiency Ratio
El.	Electrical
EV	Electric Vehicles
FCR	Frequency
GHG	Greenhouse Gas
GWP	Global Warming Potential
HHV	Higher Heating Value/Gross Calorific Value
HP	Heat Pump
ID	Intraday
LPG	Liquefied Petroleum Gas
KC	Key Characteristic
KPI	Key Performance Indicator
LiBr	Lithium Bromide
MES	Multi Energy System
mFRR	Manual Frequency Restoration Reserve
n.a.	Not available
NG	Natural Gas

OPEX	Operational Expenditures
ORC	Organic Rankine Cycle
P2G	Power-to-Gas
P2H	Power-to-Heat
RE	Renewable Electricity
RR	Replacement Reserve
TES	Thermal Energy Storage
Th.	Thermal
TRL	Technology Readiness Level
RES	Renewable Energy Sources
WWHP	Water-Water Heat Pump
WWTP	Waste Water Treatment Plant

2 Introduction

2.1 Scope of the document

The overall goal of MAGNITUDE is to design and develop business and market mechanisms as well as supporting coordination tools to enable an improved level of flexibility for the European electricity system, by increasing and optimizing synergies among electricity, gas and heat systems.

Multi-energy coupling - or sector coupling - technologies and their combinations have potentials to provide flexibility to the electricity system through synergies with heat and gas networks. In this perspective, Deliverable D1.2 aims at:

- Gathering, from the 7 project case studies and consortium's partners, the data needed to quantify the economic and technical indicators to support the simulation and optimization activities as well as the development of the market and aggregation platforms, carried out in other Work Packages.
- Evaluating the expected development in the consortium countries until 2030 of the technologies described in Section 4, in terms of technological improvements and expected spread. The evaluation is also done with respect to the requirements to provide the services identified and benchmarked in Deliverable D3.1 (Cauret, et al. 2019).
- Producing a synthetic factsheet describing the flexibility services which can be targeted for each identified sector coupling technology and technology coupling, based on current and finished projects, available studies, manufacturer data, and the participation of the MAGNITUDE Advisory Board members.
- Detailing the current and expected technical constraints that could determine variations of the calculated flexibility ranges in each country, in accordance as well to the market aspects summarized in D3.1.

2.2 Methodology

To ensure that information collection is consistent for every case study, a questionnaire was developed and sent to the Case Study (CS) owners. Once the completed questionnaires were collected and evaluated, a factsheet template containing a list of technical and economic Key Characteristics (KCs) required for the simulation and optimization tasks and for the development of the aggregation platform was proposed (see Section 3.3).

The factsheet template was then filled out for the identified sector coupling technologies, based on literature data and, when present in one of the project's case studies, with specific data about their integration.

Workshops with the contact points of the case studies were organized to integrate the data collection.

An analysis of the information included in the factsheet was carried out to assess the flexibility potential of each technology (see Section 5.2) and identify the services and products (based on Deliverable D3.1) that are the most suited for the considered technologies.

Bottlenecks and limitations to flexibility provision, due to national regulations and local specificities (e.g. demand patterns and characteristics, case studies configurations, present contracts, etc.) are described in Section 5.3.

Finally, the current and expected technical constraints and developments of each technology as well as improvements in terms of flexibility provision considered for each case study are described in Section 5.4.

The methodology followed to carry out the work presented in this document is summarized in Figure 3.

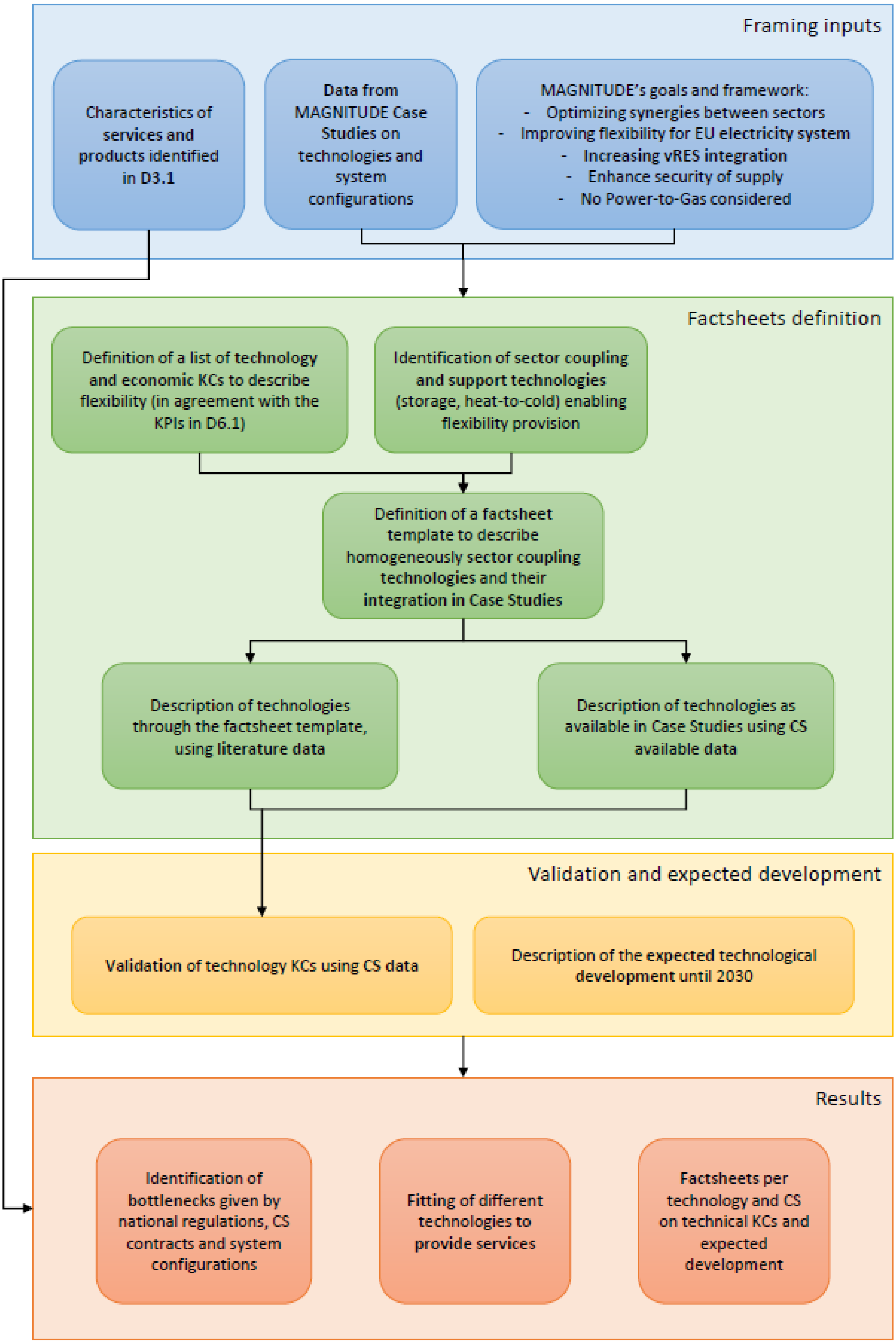

Figure 3: Workflow of the methodology applied in Deliverable D1.2

2.3 Link to other deliverables

The work presented in this deliverable is a follow-up of Deliverable D1.1 (Li, et al. 2019).

The main objective of this report is to characterize qualitatively and quantitatively the flexibility properties of each technology taken alone or in a specific system configuration.

The results will be used in the simulation and optimization tasks as input information for the modelling and optimization of Multi-Energy Systems (MES) and the quantification of flexibility.

The aggregation platform will then use this information to optimize the management of flexibilities and make forecasts of the technologies' flexibility potential and price.

The diagram below summarizes inputs and outputs of the present work.

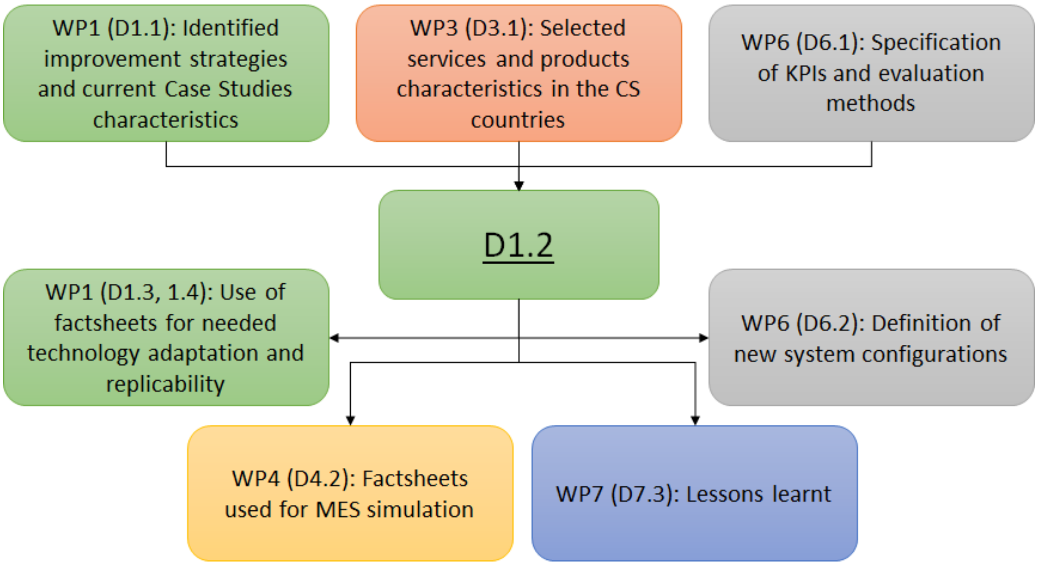

Figure 4: Links between D1.2 and other MAGNITUDE deliverables

3 Perimeter of the analysis and factsheet template

This paragraph aims at:

- Describing the sources of information used to describe technologies and technology couplings.
- Defining the perimeter of the analysis done in this document.
- Presenting the template developed to describe stand-alone and coupled technologies (as in the project case studies) through factsheets.

3.1 Case Studies

The entire MAGNITUDE project is based on a set of representative real-life cases, which allow the analysis of all main "interconnection technologies" between heating/cooling, gas and electricity networks.

The seven real-life case studies differ from each other in core business, installed technologies, operating strategies, and external boundary conditions (contracts, demand characteristics, regulatory framework, etc.), as summarized in Table 1 and Table 2.

Table 1: MAGNITUDE Case Studies: countries and categories

#	Case study	CS Acronym	Country	Category
1	Mälarenergi	ME	Sweden	District Heating and Cooling system
2	Paper mill	PM	Austria	Industry
3	Hofor	HO	Denmark	District Heating system + Individual units
4	ACS	ACS	Italy	District Heating system + Large commercial and public sites
5	Neath Port Talbot	NPT	United Kingdom	Industry + Large commercial and public sites
6	EMUASA	EM	Spain	Industry
7	Paris Saclay	PS	France	District Heating and Cooling system + Individual units + Large commercial and public sites

Table 2: MAGNITUDE Case Studies: installed sector-coupling and storage technologies

Case Study	Technologies									
	Biomass boiler	Gas boiler	Steam turbine	Gas turbine	Gas engine	Chiller	Heat pump	Electric boiler	(Bio-)Gas storage	Thermal Energy Storage
1 - ME	■		■			■	■			■
2 - PM	■	■	■							■
3 - HO							■	■		■
4 - ACS		■			■		■	■		■
5 - NPT	■	■	■	■						
6 - EM		Biogas			■				■	
7 - PS		■					■			■

The current interactions between technologies and demand in the project's case studies can be summarized as follows:

1. Mälarenergi: biofuel (woodchips, peat, tail oil, Municipal Solid Waste) fired cogeneration plants (steam turbines) supply heat to a District Heating (DH) network and inject electricity in the grid. The heat circulating in the DH network is also used to supply a District Cooling network through absorption chillers. Thermal storage allows an optimized heat production from the Combined Heat and Power (CHP) plants.
2. Paper Mill: steam turbines, supplied by gas-fired steam boilers, provide steam and electricity to the paper production process. Additional electricity is taken from the grid and excess steam is either stored in a steam storage or, in another production line, condensed and recovered in a DH network.
3. Hofor: the district heating network is connected to the city's heat distribution network. The case study includes booster heat pumps in substations to produce domestic hot water (with storage tanks) and water heaters in townhouses to provide fuel shift flexibility to the DH network, compatibly with the DH demand.
4. ACS: a gas fired CHP is run during night hours to fill thermal storages, to smooth the morning demand peak. During the day, the heat is supplied by the gas CHPs (engines) and the thermal storage and, during the heating season, by a base-load heat pump. An electric boiler will be added. The operations are always heat driven.
5. Neath Port Talbot: an industrial park including solar and wind power generation, a gas and biomass combined cycle gas turbine, and several industrial and tertiary demand sites.
6. EMUASA: biogas engines cogenerate the heat and the electricity required for the wastewater treatment processes. Additional heat, when required, is produced by a gas boiler and electricity is supplied by the grid. The biogas is produced in fermenters and a part of it is upgraded for biofuels production.

7. Paris Saclay: a geothermal doublet and peak gas boilers supply a low-temperature DH network. Heat pumps and gas boilers placed in central substations raise up the water temperature for Domestic Hot Water (DHW) production and lower it for air conditioning. Heat storages contribute to the system's flexibility.

Depending on the case study category, several flexibility levers can be activated through technology coupling:

- Industries: fuel shifting between gas and/or heat (or cooling) and electricity and internal energy storage capabilities; subjects to the process' demand;
- Big stakeholders: fuel shifting and energy storage capabilities; delivering to final consumers;
- District Heating/Cooling systems: fuel shifting and energy storage capabilities (centralised, decentralised, implicit – e.g. networks and buildings' envelope); delivering to final consumers;
- Individual units: possible energy storage capabilities (explicit or implicit) and limited or no fuel shift capability; delivering to final consumers.

3.2 Technologies

As described in Section 2.1, the scope of this document is to describe the capability of sector coupling technologies to provide services to the electricity system, either producing electricity, converting electricity into other energy carriers (heat, gas), in order to store electricity or reduce, increase or shift electricity demand when beneficial to the electricity system.

In accordance with the services and needs of the electricity systems identified in Deliverable D3.1 (Cauret, et al. 2019), from the perimeter of the analysis are excluded:

- Direct electricity storage, not in the scope of MAGNITUDE project;
- Power-to-Fuels and Power-to-Gas technologies, producing hydrogen as final or intermediate energy carrier, excluded by the project call;
- Seasonal energy storage technologies, as the provision of the identified services mainly implies an increase, decrease or shift of the energy production and consumption in the timeframe of one or a few days.

The identified sector coupling and storage technologies are described in Table 3 and have been grouped according to the type of interaction with the electricity system:

- *Power consumption and production technologies*: such devices can actively, or directly, provide flexibility to the electricity grid by increasing or decreasing their production or demand of electricity;
- *Supporting technologies*: storage technologies and conversion from heat to cold. Such devices, on the other hand, are coupled with consumption and production technologies in order to passively, or indirectly, provide additional required flexibility by storing energy or converting thermal energy produced by power-to-heat units.

The list of technologies proposed in the following table has been submitted to and validated by the Members of the Advisory Board of the project.

Table 3: Technologies described in the factsheets

#	Technology
Power consumption	
Power-to-Heat	
1	Heat pumps
2	Electrical boilers
Power-to-Cold	
3	Compression chillers
Power production	
Heat-to-Power	
4	Organic Rankine Cycle
5	Steam turbines
Gas-to-Power	
6	Gas engines
7	Gas turbines
Supporting technologies	
Storage	
8	Thermal storage: Hot water & Steam
9	Gas storage / Gas upgrading
Heat-to-Cold	
10	Sorption chillers

3.3 Technology and Case Study Factsheet template

In order to describe consistently the identified technologies and their integration in the case studies, a template of factsheet was developed.

Each technology is described through a list of Key Characteristics (KCs), in accordance with the KPIs defined in Deliverable D6.1 (Syrri, et al. 2019) and which are required for the simulation and optimisation tasks and the aggregation platform developed in MAGNITUDE. The chosen parameters are as well fundamental to assess if a technology and a technology coupling can be suitable for the provision of a certain service to the electricity system (see Section 5.1) and if aggregation is necessary for this purpose.

The complete factsheet template is available in Appendix A1 and it includes:

- KCs aiming at quantifying the flexibility capability of the technologies;
- Environmental KCs: CO_2 emissions;
- Economic KCs: CAPEX and OPEX.

The template was then adapted to take into account the characteristics of storage technologies.

Additionally, since the flexibility capability of stand-alone technologies is then influenced and determined by the characteristics of the system in which they are integrated (e.g. demand profiles, availability of storages, system inertia, etc.), a “Case studies factsheet” template was developed. This includes specific Key Characteristics further describing the performances of the technologies as they are coupled and integrated in the project’s Case Studies (see Appendix A1).

In Section 4, the information collected through the technology and case studies factsheets is summarised and commented. The proposed analysis is articulated into the following chapters:

- Technology description: working principle of the technology.
- Flexibility: flexibility levers which can be activated for the technology and quantification of the main flexibility indicators (based on literature and case studies data – when available).
- Technical barriers: factors currently preventing the exploitation of the theoretical flexibility offered by the analysed technologies.
- Expected development: summary of the technological development expect by 2030, based on European technology roadmaps and national plans.
- Potential for case studies: characteristics of the technologies installed in the Case Studies and following description of the most promising solutions and improvement strategies to further exploit the flexibility potential made available by these system configurations.

4 Technology description

4.1 Power consumption

4.1.1 Power-to-Heat

4.1.1.1 Heat pumps

Heat pumps (HPs) transfer heat from a low-temperature source to a high-temperature sink. HPs consists mainly of two heat exchangers for evaporation and condensation of a refrigerant, a compressor and an expansion valve. The refrigerant in a closed circuit is vaporized by the external heat (3), electrically compressed and thus heated (4). By releasing heat into the heating circuit, the refrigerant is cooled, condensed and finally liquefied again (1). Pressure decrease via the expansion valve (2) leads to further cooling. Then, the refrigerant can absorb heat from the source, and the cycle starts again (VDE 2015). This working principle is shown in Figure 5.

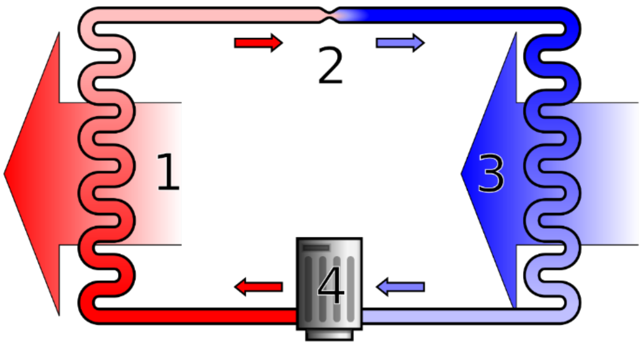

Figure 5: Heat pump scheme (Wikipedia 2019)

Many different sources of heat are utilized: ambient or exhaust air, underground water, water from lakes, rivers, the ocean or sewage water systems, and all kinds of waste heat. Heat sinks are either individual heating systems of buildings, district heating networks or industrial applications.

In general, 60-80% of the released heat is from the heat source; the consumed electricity to run the compressor, pumps and auxiliary equipment provides the remaining energy share (VDE 2015). The efficiency of a HP is given by the dimensionless coefficient of performance (COP; ratio of useful heating provided to work required), which is mainly determined by the heat difference between source and heat sink. Theoretically, COPs of 20 are possible for very small heat differences. However, the auxiliary electricity consumption for pumps, fans and compressors, transfer losses in the heat exchangers as well as the used refrigerant have a significant impact on the real COP. Therefore, only about 50% of the theoretical COP of a HP is achieved in reality (VDE 2015). Practical COPs vary broadly, e.g. air-water heat pumps at very cold outside temperatures achieve only one (acting like an electrical boiler). Actually, a COP of 4-5 is considered as very good, but values around 10 can be achieved in an appropriate system.

Air-water-heat pumps use ambient heat from the air and they are very common for buildings as well as district heating systems. However, their COP is often lower than for water-water HPs, because the heat source temperature varies over the year and, in particular during the heating period, because of the increase of the temperature difference between source and sink. Therefore, the annual average values are between 2 and 3.

Water-water heat pumps rely on water sources from the underground, rivers, lakes, seaside or wastewater. The temperature variation is much lower than for ambient air, which enables a better performance thanks to better system integration; so, higher COPs between 4 and 5 are often achieved (VDE 2015).

Generally spoken, the lower the temperature differences are between source and sink, the higher the efficiency is. Therefore, a constant high heat source temperature in combination with a low heat sink temperature are favorable, whereas varying and low heat source temperatures decrease the efficiency.

Heat pumps provide usually temperatures 40-90 °C, but HP development to provide higher temperatures is ongoing fast. Some HPs providing heat of above 100 °C and 140 °C are already being tested and installed. This development will broaden the field of application to many industrial processes and district heating networks running with superheated water (Danish Energy Agency 2016).

The capacity of HPs ranges from 2 kWth for single-family houses to 30 MWth for integration in district heating and industrial processes.

The investment costs for heat pumps are generally higher than for fuel-based or electrical boiler, whereas the operational costs are typically lower. Both aspects, as well as the additional costs for integration in heating system, require a very careful calculation of the economic viability of HP installations.

Flexibility

HPs provide several units of heat per unit of electricity consumed, making them much more efficient than other Power-to-Heat (P2H) technologies. Therefore, HPs are typically integrated in heating systems of buildings, DH systems or in industrial processes with a continuous heat demand. Therefore, the flexibility potential is determined by the heat demand of the overall heating system.

If HPs are part of a multi-source heating system, e.g. a DH network with boilers and heat storage, HPs can take over the heat supply, or at least a part of it. Heat storage or back-up boilers are however recommended for guaranteeing the satisfaction of the heat demand. From the perspective of the electricity system, HPs can be run in a way to stabilize the electricity grid.

The main Key Characteristics which characterize their flexibility behavior are detailed in Table 4.

Table 4: Technology Factsheet –Heat pump

Parameter	Unit	Value
Power output	MWth	0.002-30
Operating temperature level input	°C	-20 - +50
Operating temperature level output	°C	30-100
Minimum load	%	10
Controllable range	%	10-100
COP	-	2-5 (practical) 1-20 (theoretical)
Cold start up time	min	300
Hot start up time	min	3
Ramp rate up/down	% nom power/min	20
Specific investment costs	€/kWth	500-1 800

Technical barriers

HPs are usually not designed to switch on or off very often. Due to the mechanical parts inside the HP, too many start-ups/shut-downs increase abrasion and so lower the lifetime significantly (generating additional maintenance costs) (Prognos 2011). In the recent years, improvements have been done to run HPs more flexibly, e.g. via inverter technologies.

A major barrier to a wide deployment of heat pumps is the currently changing regulation on refrigerants. In more and more European countries, synthetic refrigerants based on fluorinated hydrocarbons are forbidden due to their very strong negative Global Warming Potential (GWP) effects. Therefore, new low GWP refrigerants are developed, tested and applied in heat pumps, e.g. NH_3, CO_2 or natural carbohydrates (often flammable or requiring higher operating pressures). However, their thermodynamic properties differ compared to previously used refrigerants, which requires adaptation of compressors and exchangers to ensure the same performances. Therefore, further R&D efforts are required.

Expected development

Heat pumps are an energy efficient heating technology, fully in agreement with EU climate and energy goals (David 2017). Studies estimated a potential increase of the DH share to 50% of the entire heat demand by 2050, with approximately 25–30% of it being supplied using large-scale electric heat pumps. So far, most large scale HPs are custom-made, so a significant cost decrease potential is available. The numbers of new HP installations is assumed to increase strongly within the next decade (IRENA 2013). For Northern and central European countries, the efficiency of HPs is estimated to increase only slightly, but a much bigger effect will be seen as a result of a wider integration into heating networks, as can be observed actually for new large HPs. Therefore, overall performance are supposed to increase by 40-60% till 2050, in parallel with a cost reduction by 30-40% (IRENA 2013).

Furthermore, the introduction of alternative refrigerants will proceed: the currently experienced difficulties will have a lower impact in the future; on the one hand thanks to legislative support and, on the other hand, by increasing return of experience with such systems.

Finally, HPs are in competition with fuel-based technologies; therefore, the fuel-electricity price-ratio is a crucial parameter. Whereas the electricity price is expected to increase slowly, an envisaged CO_2 price for fossils fuels would lead to better economics for HPs. A decreasing CO_2 grid factor would also be advantageous.

Potential for case studies

Several HPs are installed in the MAGNITUDE case studies:

- two large heat pumps at Mälarenergi, coupling the District Heating and the District Cooling networks;
- one large water-water heat pump at ACS;
- two small booster HPs (single stage compression HP units) to match the temperature requirements of the heat demand profile of a multifamily building in HOFOR, together with an underground water heat pump in the cruise terminal;
- one large underground HP as well as 7 semi-centralized HPs will be installed for District Heating and Cooling (DHC) purposes in Paris-Saclay.

Their provided KCs are shown in Table 5.

Table 5: KCs provided by case study owners for heat pumps

Parameter	Unit	Mäla-energi	ACS	HOFOR (cruise terminal)	HOFOR (DH substation)	Paris-Saclay (planning state)
Power output	MWth	2x12 (Heat) 2x10 (Cold)	18 (heat) 13.7 (cold)	0.8	n.a.	37
Power input	MWe	n.a.	6	0.25	0.003	7x0.355 +1x10
Operating temperature level input	°C	n.a.	65	10	25	30 (small) 10 (big)
Operating temperature level output	°C	70	90	75	65	63
Minimum load	%	n.a.	3	3	n.a.	30
Controllable range	%	n.a.	3-100	3-100	n.a.	1-100 (several set points)
COP	-	n.a.	2.7	n.a.	4	3
Cold start up time	min	n.a.	10 min	n.a.	n.a.	n.a.
Hot start up time	min	n.a.	0	n.a.	n.a.	n.a.
Ramp rate up/down	% nom power/min	n.a.	n.a.	n.a.	n.a.	n.a.
Specific investment costs	€/kWth	n.a.	n.a.	n.a.	n.a.	n.a.

At HOFOR, the cruise terminal HP is part of an integrated multi-source heating system including an electric boiler, a HP, heat storage and an oil back-up furnace (Figure 7). The flexibility potential is estimated to 50 kWe/min (20% ramp rate of the power input in MWe*)*, as within the system, heat could be provided easily by alternative heat suppliers. Similar considerations lead for ACS to a flexibility potential of 1 200 kWe/min.

Furthermore, for the Austrian paper mill, a HP is also envisaged as an additional piece of equipment for future configuration improvement, as it could provide drying energy at the required temperature level.

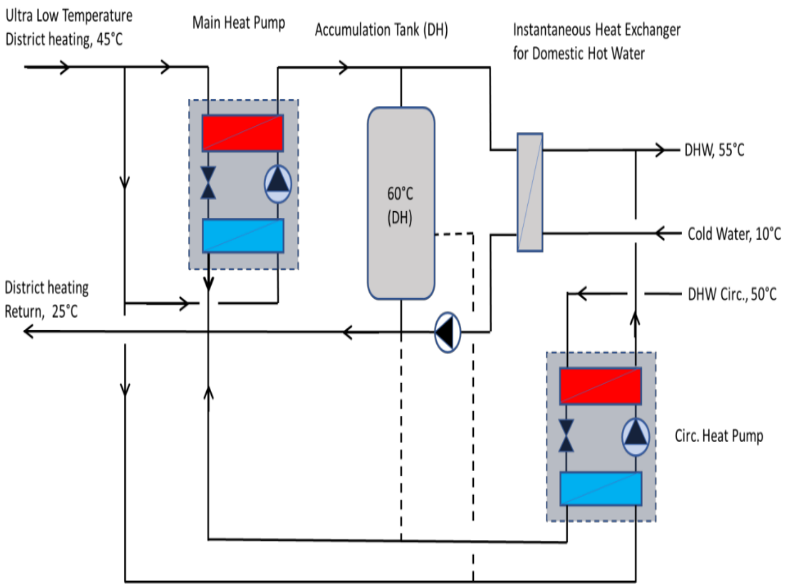

Figure 6 : Basic Layout of the Heat Booster substation in a multi-family building (Thorsen and Ommen 2018)

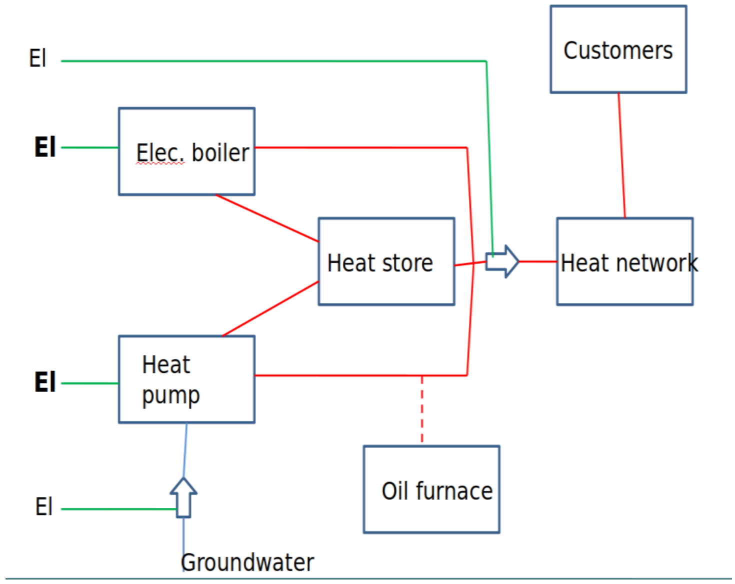

Figure 7: HP integration scheme in the HOFOR case study; electricity flows in green (El); heat flow in red (with the permission of Hofor [https://www.hofor.dk/] and EnergyLab Nordhavn project [www.energylabnordhavn.dk])

4.1.1.2 Electrical boilers

Electrical boilers are a mature technology, well established in Scandinavia and Germany thanks to electrical grids coping with growing shares of intermittent wind & PV generation. In Denmark, large boilers are used predominantly for primary grid regulation; so, the whole capacity of the boiler is bid in for negative grid regulation thanks to the short required ramp up times (Danish Energy Agency 2016). In other countries, notably Germany, a market has developed for large electrode boiler in negative secondary regulation applications, i.e. absorbing power from the grid, but over longer periods (VDE 2015). Furthermore, small electric boilers are used to provide heat and domestic hot water for single and multi-family houses.

There are two types of electric boilers: resistance and electrode ones. Depending on the size, resistance boilers are used in individual heating systems or for DH, whereas electrode boilers are only used for DH due to their larger heat production capacities. Steam production for industrial processes is also possible with both types, but the specific costs are increased significantly; so, this solution is not yet very widespread.

Electric resistance heater

Electrical resistance heaters convert electricity into heat that is stored in water. The heating elements are integrated either into a hot water tank (heating rods), or into the heater circuit (electric flow heater). The functional principle is similar for both types: heat is produced when electricity passes through the heat wire element due to the electrical resistance (VDE 2015). Within heating circuits, the heating of the flow water is done via multitudes of resistance heating elements. The resistance heating elements are grouped together, so they can either be switched in steps or stepless controlled by power controller.

The capacities range from a few kW for heating rods up to 1-10 MW for flow heaters to provide warm and hot water for industrial or DH applications (VDE 2015).

The main flexibility KCs of the resistance heaters are presented in Table 6.

Table 6: Technology Factsheet - Resistance Heater

Parameter	Unit	Value
Power output	MWth	0.005-10
Operating temperature level input	°C	50
Operating temperature level output	°C	70-140 (steam possible; but not common)
Minimum load	%	1
Controllable range	%	1-100
Net Thermal Efficiency	%	99
Cold start up time	Min	5 (but no common use)
Hot start up time	Min	<0.5
Ramp rate up/down	% nom power/min	100
Specific investment costs	€/kWe	30-150

Technical barriers

There are no technical barriers which prevent the use of resistance heaters for flexibility services provision, since, also from the point of view of the connection to the electricity grid, only a low voltage (400/650V) connection is required (VDE 2015). The complexity of the power control is closely connected to the thermal capacity, due to the amount of heating elements. Therefore, sizes > 2 MW are not very common. A minimum electrical load is required to enable the very fast ramp-up times, which lays in the order of magnitude of seconds (Prognos 2011).

The optimum temperature spread between input and output flows is about 40-50 °C. However, for most widespread small heaters, the capacity is a critical issue. The sizes do not fit to market requirements for grid services provision (see Section 5.1), unless aggregation is put in place.

Expected development

The International Energy Agency estimates the European P2H potential to be as high as 100 GWe in 2020 and 150 GWe in 2030, whereas the DH sector is estimated to increase up to 50% till 2050 for the overall European heat demand (David 2017). Therefore, taking into account the good compatibility with the variable RES production, an increased number of resistance heaters can be expected.

Small resistance heaters (5-30 kW) are used for building heating, in particular for hybrid heating systems. In particular, a combination of resistance heaters fed by the self-consumed electricity provided by photovoltaic panels is a very good option, especially to tackle decarbonization of the heating sector.

The barriers related to the small capacities make them - similarly to heat pumps - a very promising subject for aggregation, i.e. for clustering several units into "virtual" large capacity by taking still advantage of the very fast response times. Therefore, an increase of installations is expected, which will be followed by a decrease of the specific costs thanks to economy of scale (Prognos 2011). The number of larger resistance heaters will also increase, thanks to the expected development of the DH sector.

Because the technology is mature, only a moderate potential for optimization of costs and efficiencies is foreseen (Danish Energy Agency 2016).

On the other hand, further developments to improve the dynamic behavior of large resistance heaters can be expected, also to enhance the flexibility of their combination with renewable electricity production technologies and CHPs optimizing self-consumption.

Potential for case studies

Electric boilers are installed in two case studies so far: ACS and Hofor. At ACS a big resistance heater (10 MWth) is installed, whereas at HOFOR two smaller units (each 0.113 MWth) are implemented (as part of the cruise terminal configuration) and also small units in a series of single row houses.

The provided KCs for both case studies are given in Table 7.

Table 7: KCs provided by case study owners for electric resistance heaters

Parameter	Unit	ACS	HOFOR (cruise terminal)	HOFOR (single row houses)
Power output	MWth	10	0.113	0.003
Operating temperature level input	°C	60	20	10
Operating temperature level output	°C	90	95	60
Minimum load	%	0.03	n.a.	n.a.
Controllable range	%	0.03-100	n.a.	n.a.
Net Thermal Efficiency	%	99.5	n.a.	n.a.
Cold start up time	min	10	n.a.	n.a.
Hot start up time	min	2	n.a.	n.a.
Ramp rate up/down	% nom power/min	5-10	10	n.a.

Electrode boiler

Figure 8 shows the principle scheme of a steam generating electrode boiler. The boiler consists of two chambers, the inner and an outer container. The inner one contains the two electrodes, which are supplied with Alternating Current (AC) from the medium voltage grid (5-20 kV).

The current between the two electrodes heats up the water due to the ohmic resistance of the water. The output is controlled step-less by variation of power and contact area between water and the electrodes (Prognos 2011).

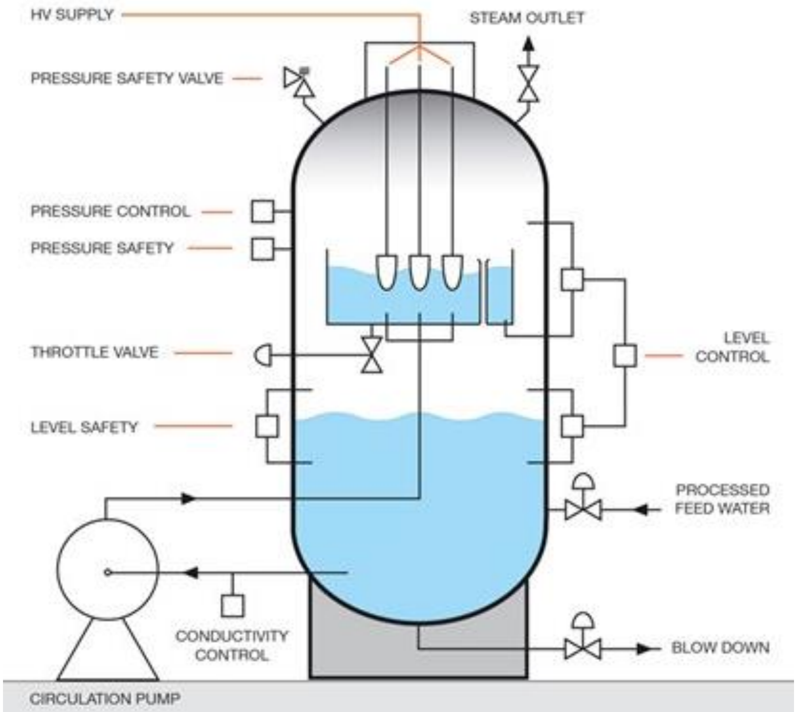

Figure 8 : Scheme of an electrode boiler for steam generation [© Parat Halvorsen AS] (PARAT 2018)

The KCs describing electrode boilers are summarized in Table 8. These are similar to the values of the KCs referring to resistance heaters, although steam production broadens the possible applications.

Table 8: Technology Factsheet - Electrode boilers

Parameter	Unit	Value
Power output	MWth	5-60
Operating temperature level input	°C	50
Operating temperature level output	°C	Water: 70-140 Steam: <300 at 45 bar
Minimum load	%	1-5
Controllable range	%	1-100
Net Thermal Efficiency	%	99
Cold start up time	Min	5
Hot start up time	Min	<0.5
Ramp rate up/down	% nom power/min	100
Specific investment costs	€/kWth	40-100

Flexibility

Due to high electricity price compared to the low gas price, provision of base load heat is actually not economic so far. However, the flexible provision of heat is very common with electrode boilers, which are with their minimal pipework and no heating surfaces very well suited to fast ramping. The response times to full nominal capacity are very fast; a minimum load of about 1% nominal capacity is required to keep the boiler operational (Danish Energy Agency 2016). Electrode boilers can provide either warm or hot water as well as steam (up to 300°C and 30 bars) with efficiencies above 99% and capacities of 5-60 MW (PARAT 2018). The precise controllability, the fast load gradient and the fully automatically controllable operation make it possible to control all types of regulating power: primary, secondary up to minute reserve capacity (Prognos 2011).

Specific investment costs are about 40-100 €/kWth for a stand-alone boiler. Due to additional implementation costs into the existing heating infrastructure, overall specific investment costs are estimated about 100-300 €/kWth for DH and 125-350 €/kWth for industrial steam networks (Danish Energy Agency 2016).

Technical barriers

Electrode boilers are also a mature technology. Important requirements are a medium-voltage power grid connection and a temperature difference of about 40K between hot and cold flows, as well as an appropriate heat sink, consequent to the large heat capacities (Sterner 2017). (Prognos 2011) estimates as minimum size a steam networks with more than 20t/h steam consumption for integrating electrode boilers, due to buffer needs for intermitting steam production. Finally yet importantly, electrode boilers require an electrical conductivity within the water of about 60µS/cm^2, therefore, water preparation is mandatory.

Expected development

Similar development trends as for the large resistance heaters above can be expected: improvements in the dynamic behavior, moderate cost decrease and a growing market due decarbonization of the heating market and the increase of intermittent renewable electricity production. In contrast to resistance heaters, electrode boilers are also used to provide high temperature steam. Therefore, the future market size is larger; beside DH networks, industrial steam networks represent another field of application.

Potential for case studies

Actually, no case study has an electrode boiler running. However, ACS, Mälarenergi and the Austrian paper mill appear to be suitable for the future installation of this technology, thanks to their large DH and steam networks.

4.1.2 Power-to-Cold

Compression chillers

Flexibility

Chillers have many applications, from commercial to industrial ones: they are used as air conditioning systems and for the cooling of industrial processes, and recently district cooling or hybrid heating/cooling networks have become increasingly popular.

There are two basic types of chiller cycles: vapor compression and sorption. Sorption systems are thermally driven chillers; however, they are mainly used if surplus of non-expensive heat is available (see Section 4.3.3). Vapor compressors use reciprocating, screw or centrifugal compressors to supply the refrigerant circuit. Compressors are usually powered by electric motors, although they can also be driven by gas engines or steam turbines. Electrically driven chillers are the most popular systems to provide cold.

Compressor chillers are an example of Power-to-Cold coupling, as they use electricity to drive a compressor that moves the refrigerant in the cooling circuit.

Compression chillers are divided into two groups: air-cooled and water-cooled units. Both types have the same operating principle and basic components, which are an evaporator, a compressor, a condenser and an expansion valve. The only difference is how the heat is extracted from the system, i.e. using water or air.

In the case of an air-cooled chiller, the air flows through exposed condenser tubes that evacuate heat. Water-cooled chillers have a sealed condenser and the water is pumped to dissipate heat and disperse it through the cooling-tower, which is usually equipped with fans that help to reject heat from the system. Water-cooled units are more complex in installation and maintenance but they are smaller than the air-cooled units, which require outdoor location and whose efficiency is more affected by external conditions. In addition, water-cooled units have higher full and part-load efficiency (Johnson Controls 2015).

Air-cooled compression chillers are available in sizes ranging from 0.1 (domestic) up to 1 750 kWth and water-cooled chillers are available in sizes ranging from 21 to 21 100 kWth. Performance of the units is defined through an Energy Efficiency Ratio (EER), which is the ratio between the total cooling capacity of the device and the power consumption of the compressors or fans. EER for the air-cooled units lays between 2.6-3.24 and for water-cooled chillers between 4.0-6.31 for full load operations (Florida Power & Light Company 2019). For partial load operation, the EER depends on the load and the way in which the compressor drive is run, with a constant speed or a variable speed. Variable speed units better adjust to changing conditions and different operating needs and can reach EER up to 12 (see Figure 9) (Johnson Controls 2018). The minimum load for compression chillers is about 20%, and 85% of time chillers operate within 30 and 85% of nominal cooling capacity (Johnson Controls 2015). The time to ramp up to full load is ranging from 20 min up to 45-60 min, which gives an increase of 1.6-5% of nominal power per minute.

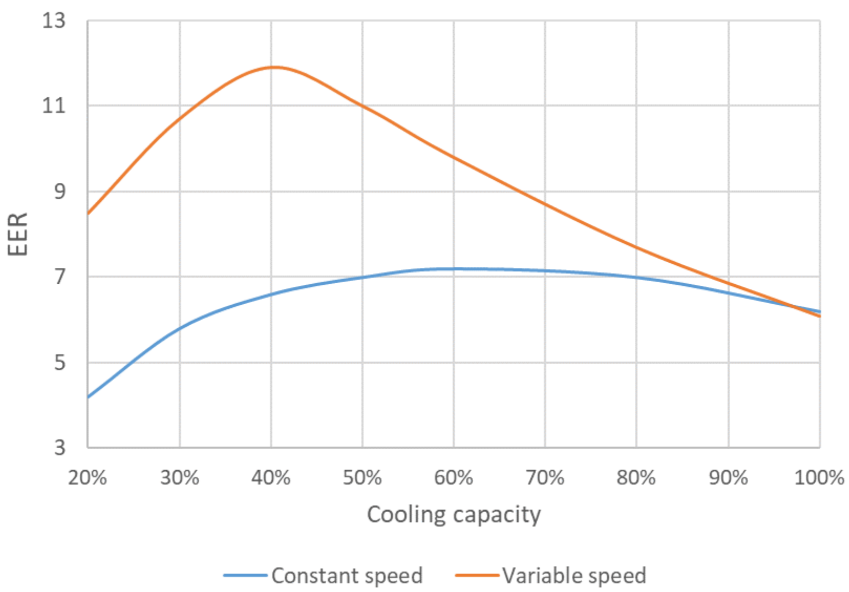

Figure 9: Energy efficiency ratio versus cooling capacity. Own drawing based on (Johnson Controls 2018).

Table 9: Technology Factsheet- Compression chiller (Johnson Control 2019, Johnson Controls 2015, Johnson Controls 2018, Florida Power & Light Company 2019)

Parameter	Unit	Air-cooled chillers	Water-cooled chillers
Power output (cold output)	kWth	0.1-1 750	21-21 000
Operating temperature level input	°C	Depending on the needs	Depending on the needs
Operating temperature level output	°C	Depending on the needs	Depending on the needs
Minimum load	%	20	20
Controllable range	%	20-100	20-100
COP Cooling (EER)	-	2.6-3.24	4.0-6.31
Cold start up time	min	20-60	20-60
Ramp rate up/down (cooling)	% nom power/ min	1.6-5% for start up	1.6-5% for start up
Specific investment costs	€/ kWth	350 – 880 for < 530 kWth 310 – 440 for ≥ 530 kWth	220 – 310 for screw and scroll chillers 220 – 530 for centrifugal chillers < 1 400 kWth 175 – 440 for centrifugal chillers > 1400 kWth

Technical barriers

Compression chillers are mature technology and no major technical barriers are expected for their exploitation. Nevertheless, frequent compression cycles may result in increased system wear and temperature instability, which will lead to premature failures of the components. Short cycles may cause problems with lubrication, as there they do not let enough time for oil to circulate through the system. This issue may be solved by using of variable speed drives. Impact of cycling on the lifetime can be seen in Figure 10.

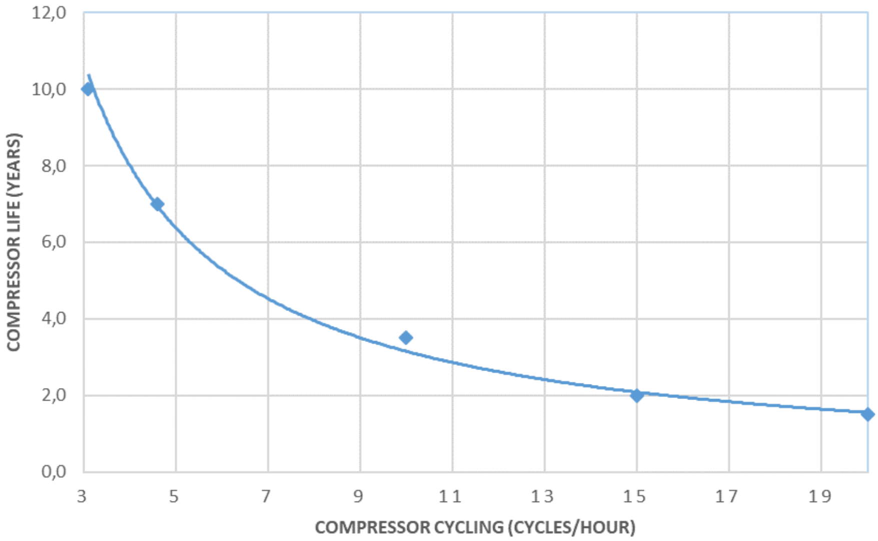

Figure 10: Impact on frequent cycling on lifetime of hermetic reciprocating compressor with 300 000-cycle design life. Own drawing based on (Laser Focus World Magazine 2004)

Expected development

Chillers are a well-developed technology. Currently, research groups are working on the development and optimization of their control strategies taking into account system-level approach.

Nevertheless, similarly to the case of heat pumps, the biggest driver for further development is the legislation, which aims at using less harmful and more environment friendly chemicals as refrigerants, such as HFOs (hydrofluoroolefins) and HFCs (hydrofluorocarbons), which may have an impact on the investment and maintenance costs. At present most of the manufacturers use R-134A as it is safe, reliable and cost effective (Johnson Controls 2015).

From a market perspective, it is expected that the cooling market in the European Union (EU) will grow in the next ten years, from 399 TWh in 2020 to 513 TWh in 2030. Therefore, it is probable that either solution based compression chillers, taking advantage of the surplus of renewable electricity (PV, Wind etc.), or on absorption chillers, taking advantage of the surplus of heat (CHP and industrial waste heat) will play a key role in the future cooling market.

Table 10: The Rescue project prognosis on cooling market development (Tvärne, Frohm i Rubenhag 2015)

Year	**2020**	**2030**
Residential (TWh)	78	95
Service sector (TWh)	321	408
Total (TWh)	399	513

4.2 Power production

4.2.1 Heat-to-Power

4.2.1.1 Steam turbines

Flexibility

Steam turbines are used to convert chemical energy of fuel into mechanical energy, which can be used either to move generators or other mechanical drives such as pumps, fans etc. Power output range is up to 1 900 MWe for nuclear power plants, up to 1 000 MWe for coal fired plants and up to 250 MWe for combined heat and power (CHP) units (Siemens steam turbine portfolio 2018, GE Power 2019, U.S. Department of Energy 2016). Steam turbines are split into three main groups: condensing, backpressure and extraction ones. Depending on the size and design of a steam turbine, we may have different isentropic efficiencies of the turbine: 53-57% for small single stage units, 60-67% for multistage units with power output < 10 MWe, and 75-90% for multistage turbines above 10 MWe. For power generation, mainly multistage condensing turbines are used with at least two turbine casings (high pressure, medium pressure). If the process requires a heat source at a higher temperature (above 70 °C) then backpressure and extraction turbines are in favour. Depending on the use, turbines may provide bigger or smaller flexibility reflected in the respective ramp up and down rates. Power-oriented units, such as steam turbines, may provide flexibility to the system in a better way than CHP units, which are mainly driven by specific customer heat needs. Situation may change significantly when steam turbines are coupled with other technologies such heat accumulators, heat pumps that may deal with surplus of heat production.

Table 11: Technology Factsheet- Steam Turbine

Parameter	Unit	Single stage		Multi stage	
		Condensing	Backpressure	Condensing	Backpressure
Power output	MWe	0.1-6	0.1-6	5-1 900	5-250
Operating temperature level input	°C	150-500	150-500	300-620	300-565
Operating temperature level output	°C	50-70	100-400	50-70	100-400
Minimum load	%	n.a.	n.a.	25-50	25-50
Controllable range	%	n.a.	n.a.	25/50-100	25/50-10
Net Electrical Efficiency	%	10-20	3-15	15-47	3-25
Thermal Efficiency	%	0	<80	0	<80
Cold start up time	min	n.a.	n.a.	240-420 (1 day for nuclear plants)	
Hot start up time	min	n.a.	n.a.	120-360	
Ramp rate up/down	% nom power/ min	n.a.	n.a.	1-8%	
Specific investment costs	€/ kWe	1 100-1 500			

Table 12: Flexibility parameters of steam turbines depending on the fuel. Based on: (Siemens steam turbine portfolio 2018, GE Power 2019, Alstom 2012, C. Grigg 1999, Miguel Angel 2018, Henderson 2014, Feldmueller 2017, Shunchao Wang 2018)

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

Technical barriers

The flexibility of a steam turbine is impacted by the coupled steam generator, its combustion technology and fuel diet. According to the values given in Table 12, solid fuels (represented as coal and lignite) provide smaller flexibility and require higher loads than liquid fuels such as oil and gas. On the other hand, nuclear plants, thanks to their huge power outputs, may be able to provide the required amount of power, but, on the other hand, they are limited by the required minimum load and are therefore generally used for baseload generation. Nevertheless, in France the nuclear power plants provide all types of frequency regulation: FCR, aFRR and mFRR.

Steam turbines are limited also by their cycling capability: on/off cycles are the main source of progressive deterioration of turbines material. Thermal and pressure stress applied cyclically accounts for the growth of existing flaws or incipient cracks, thus resulting in shortening the lifetime of turbine's and steam generator's components. To minimise the need for on/off operation, steam turbines should be run continuously taking into account the minimum allowed load.

Expected development

Current research activities focus on the development of advanced ultra-supercritical boilers that are to produce steam with parameters around 720 °C and 350 bar, thus increasing overall efficiency (N. Saito 2015). Besides the increase of efficiency, startup time is also expected to be shortened (1-4 hours depending on starting condition) and systems should be more resistant to load change cycles and be able to provide ramping rates at a level from 10%/10s to 10%/min. Achieving these goals will also require new plant control systems equipped with self-learning predictive systems (Henderson 2014).

Potential for case studies

Among the analyzed case studies there are several sites equipped with steam turbines.

For the energy production assets in Mälarenergi, the calculated value for the total theoretical ramp up potential is 25.35 MWe/min. However, almost 90% of this amount is represented by fossil-fueled peak units operated occasionally, thus the real potential is represented by the base load units (Blocks 5 and 6[1]). Ramp rate values for Block 6 were obtained from data provided by the case study owner and for Block 5 they were calculated based on the values given in Table 13, assuming that the biomass and waste are analogue to lignite. The obtained exploitable ramp up potential at the energy production site corresponds to a value of 0.55-2.95 MWe/min. The real system flexibility is however further reduced by the direct link to the heat

[1] Please refer to Deliverable D1.1 (Li, et al. 2019) for detailed information on the steam turbines available in the project's case studies.

demand of the district heating network. Therefore, in order to extract this flexibility from the system, additional technologies taking care of surplus/insufficient heat production have to be involved.

Table 13: KCs provided by case study owners for steam turbines

Parameter	Unit	Austrian paper mill – CHP- industry				Mälarenergi – CHP - District Heating Network					Neath Port Talbot	
		Line H-T1	Line H-T2	Line K-T1	Line K-T2	Block1	Block2	Block3	Block5	Block6	Steel industry	Biomass plant
Power output	MWe	5.3	10	10.8	6.4	30	30	220	60	50	95.7	14
Operating temperature level input	°C	500-505				n.a.	n.a.	n.a.	540	470	n.a.	512
Operating temperature level output	°C	190-210				n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Minimum load	%	29	23	29	29	n.a.	n.a.	n.a.	n.a.	17	n.a.	n.a.
Cold start up time	min	120	120	120	120	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ramp rate up	% nom power/ min	28	16	6.6	6.6	1-8*			1-4*	1.1	1-8*	1-4*
Ramp rate down	% nom power/ min	9	8	7.2	7.2					1.4		
Max ramp up potential	MWe/min	1.5	1.6	0.7	0.4	2.4	2.4	17.6	2.4	0.55	7.7	0,56
Total ramp up potential	MWe/min	1.5-3.1		0.4-1.1		2.4-22.4			0.55-2.95		0.56-8.26	
Additional information		Steam accumulator				Peak units			Base load			Power only
Main fuel		Natural gas		Natural gas + biomass that is a main fuel (black liquor, wood waste, bark, etc.)		Tail oil & peat	Tail oil & peat	Oil	Solid biofuel	MSW, industrial waste, recycled wood, wood, peat	Natural gas or gas from blast furnace	Biomass

***values calculated based on literature research**

Values for the Austrian paper mill are very high if compared with to the values given in Table 11 and Table 12. However, such high ramp up rate is only achievable in a limited part (30%-40%) of the full operational range and rather on higher steam input. In addition, the system configuration in the paper mill (including bypasses with pressure reduction valves, steam accumulator) enables to achieve a more dynamic operation of the system than in the case of conventional power and heat plants (Mälarenergi).

By comparing the values of the two sites constituting the Austrian Paper mill, it may be seen that the fuel diet as well as additional equipment (steam accumulator) affect the achievable ramp up rates.

However, the concrete feasibility of exploiting the full available flexibility is limited, as the energy (steam and electricity) demand of the paper production process has the priority over the energy production optimisation. In addition, the black liquor recovery boiler does not provide any flexibility, since it is run mainly at full load.

4.2.1.2 Organic Rankine Cycles

Flexibility

Besides generation by steam turbines, electricity can be generated by turbines in which blades are moved by high molecular weight hydrocarbon organic substances: they are known as Organic Rankine Cycle (ORC) systems. Their main advantage is that organic fluids have lower boiling points and higher vapour pressures compared to water thus offering a possibility to produce electricity from low-temperature sources. Because of this fact, ORCs are widely used in applications using heat sources in the range of 70 °C (Enogia 2019) to 530 °C (Triogen 2019). ORC systems are installed either as primary heat-to-power technology in bio/waste-fuelled CHP, geo- and solar- thermal plants (up to 11 MWe of electrical output) or as a secondary hybrid technology, which allows recovering waste heat streams that would otherwise be lost (an electrical output down to 5 kWe is possible). The gross electrical efficiency for ORC turbines is between 4.9-26.4% and is highly linked with the temperature difference between the heat source and the heat output (see Figure 11). Thermal efficiency represents the percentage ratio between the amount of available heat output (e.g. for a district heating) and the amount of total energy input, and can reach up to 80%. In comparison to steam turbines, ORC systems maintain higher partial-load efficiency and can operate down to 10-15% of their nominal load (see Figure 12). Startup time for an ORC system coupled with a diesel engine is around 20-30 min, which are required for pressure and temperature stabilization after the engine start up (Antti Uusitalo 2015). The ORC turbine may react to upward and downward regulation signals from the power grid, since ramp rates can reach 15-30%/min, even if typical values are about 2 to 5% of nominal power per minute (Mate 2015).

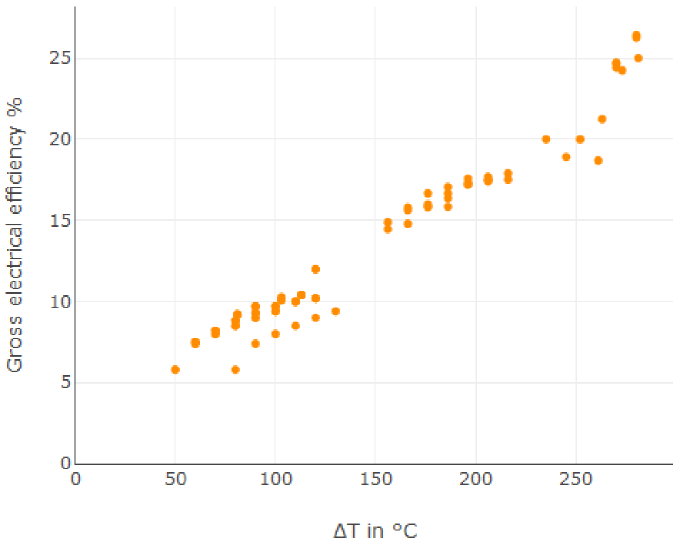

Figure 11: Gross electrical efficiency according to the temperature difference between the heat source (evaporator input) and the heat output (condenser output) (source: EIFER)

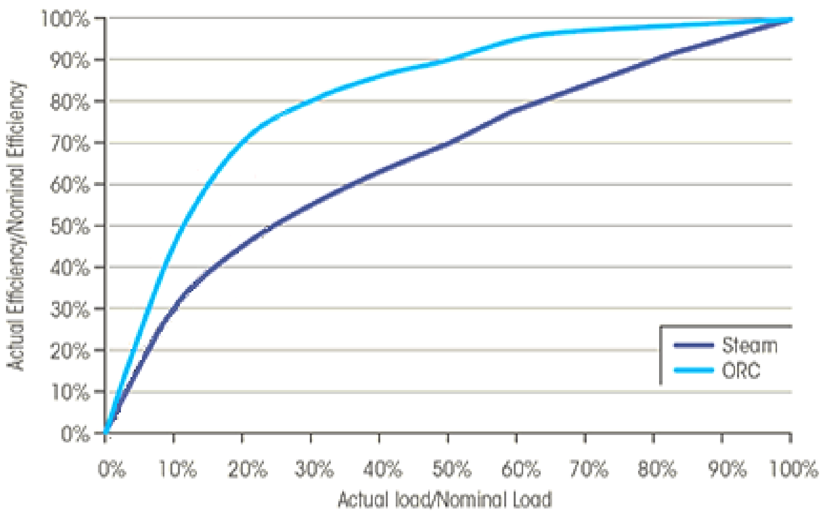

Figure 12: Direct comparison in efficiency versus load for similarly sized steam turbine generator and ORC turbogenerator (Welch and Pym 2015)

Table 14: Technology Factsheet- ORCs (Mate 2015, Siemens AG 2014, Danish Energy Agency 2016)

Parameter	Unit	Value
Power output	MWe	0.05-11
Operating temperature level input	°C	60-530
Operating temperature level output	°C	60-252
Minimum load	%	10-15
Controllable range	%	10/15-100
Net Electrical Efficiency	%	5.8-25.4

Parameter	Unit	Value
Thermal Efficiency	%	≤80
Cold start up time	Min	20-30
Hot start up time	Min	15
Ramp rate up/down	% nom power/ min	15-30 2-5 (geothermal)
Specific investment costs	€/kWe	2 300 for 500 KWe 1 400 for 1 MWe 700-850 for more than 3 MWe

Technical barriers

ORC units are typically designed for a nominal operating point, therefore they should not be operated in part load-conditions. Frequent startups of coupled engines will influence temperature and mass flow rate of the heat source, having a negative impact on the ORC performance. Therefore, additional thermal storage for ORC systems may be required in order to avoid efficiency decrease and reduce the need of frequent starts and stops (Lecompte, et al. 2017). The ORC efficiency can also be improved by implementing an appropriate control strategy, which takes into account the variability of the heat source to achieve continuous re-optimization of operating conditions (Sylvain Quoilin 2013).

Expected development

Technical development

While the current state of the art indicates maturity for the first generation of ORC cycles, significant improvement axes are still present, which require further basic research. There is still a need of improving the efficiency of the ORC cycle, analogously to the historical development of the steam cycle by working on supercritical cycles. To do so, research groups focus on working fluid selection issues, on innovative architectures of cycles and on turbine optimization (Sylvain Quoilin 2013).

In addition, there are ongoing studies regarding coupling ORC units with gas turbines in order to improve efficiencies at part-load operation. The ORC systems may utilize exhaust gases from smaller gas turbines (460-550 °C) and provide additional electricity production, resulting in a very load-flexible power plant with optimal efficiency and emissions compliance across a wide load range. This may represent an interesting option compared to a conventional large-scale Combined Cycle Gas Turbine (CCGT). Moreover, in the power range of the ORC systems, the organic based turbines have lower mechanical stress unlike single stage steam turbines. The main reason is that they can be equipped with larger diameter turbines and thus operating at lower speeds, typically 3 000 rpm compared to the around 10 000 rpm of steam turbines (Welch and Pym 2015). In addition, this coupling eliminates the need for water at all, thus providing a possibility to be installed in areas with limited water sources (Siemens AG 2019).

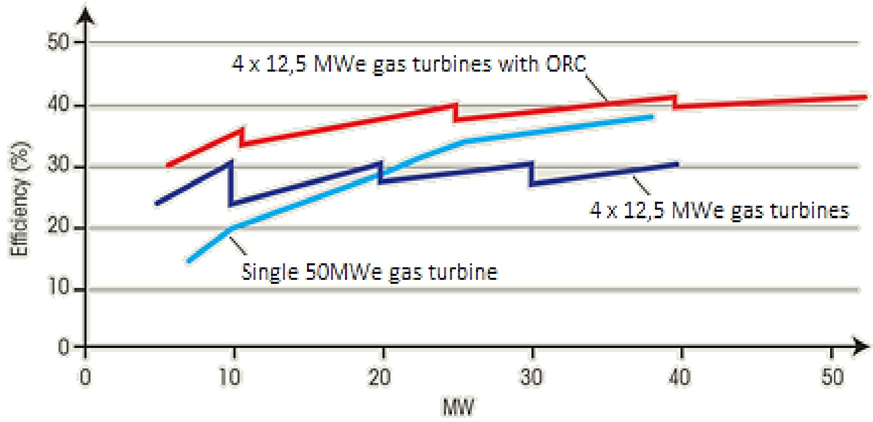

Figure 13: Efficiency versus load comparison for a 50-MW class gas turbine and 4x12.5 MW class gas turbines in open cycle with 4x12.5 MW class gas turbines with ORC at 40°C ambient temperature (Welch and Pym 2015)

When ORC units are installed at the bottom of gas turbines, they may provide up to 30-40% of additional power and up to 15% of additional generation if coupled with reciprocating engines (see Figure 14).

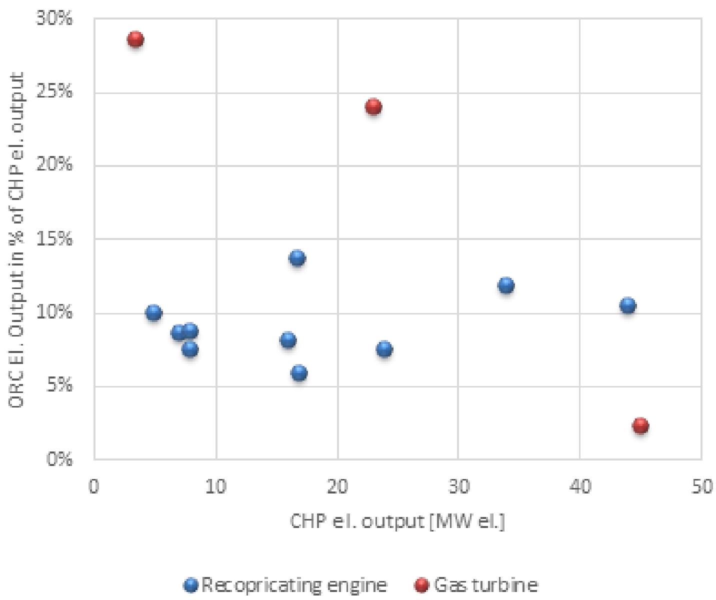

Figure 14 : Additional power generation for ORC units combined with reciprocating engines (diesel, gas) and turbine. Own drawing based on data from Turboden typical applications (Turboden 2018)

Market development

ORC systems are mainly used in geothermal plants (74.8% of all ORC installed capacity in the world). Next application areas are waste heat recovery (13.9%) and biomass plants (11%). Waste heat recovery is an emerging field with an interesting potential for all unit sizes. Solar applications are negligible mainly because of the high investment costs that makes ORC more expensive than PV-battery systems (see Figure 15).

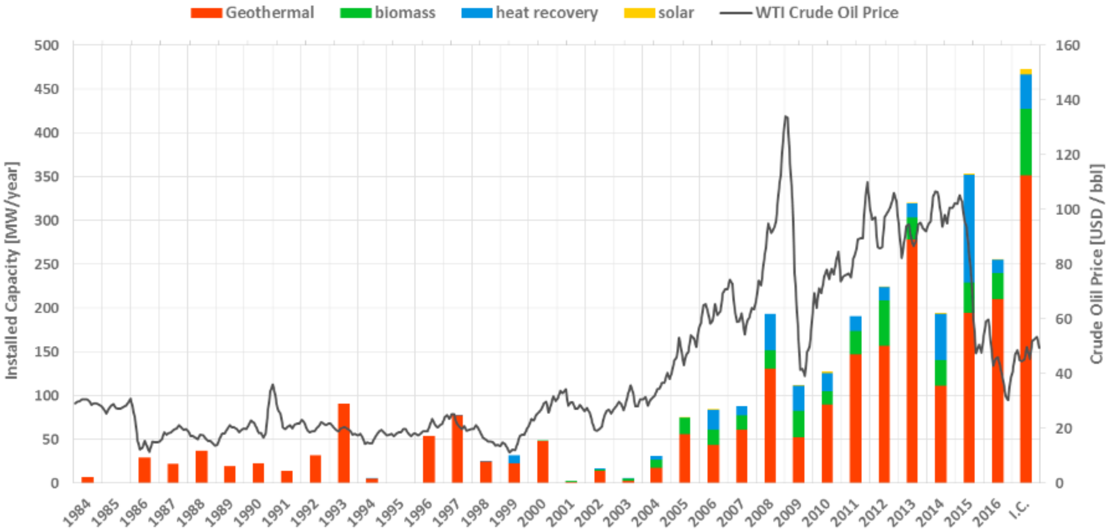

Figure 15: Evolution of installed capacity over time, per application (Tartière and Astolfi 2017)

Waste heat recovery is dominated by coupling ORC systems with gas engines or turbines, followed by waste-to-energy applications and heavy industries, which have low market shares despite their apparently large heat recovery potential (see Figure 16). It can be seen that geothermal, waste heat recovery and biomass applications experienced a fast growth over the last decade (see Figure 17) and it is expected that ORC installed capacity will continue to increase, especially in the field of waste heat recovery (circular economy concepts).

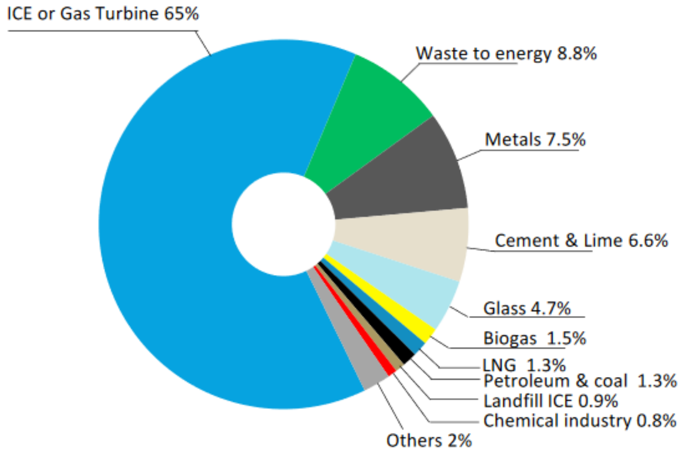

Figure 16: Shares of installed capacity per heat recovery application (Tartière and Astolfi 2017)

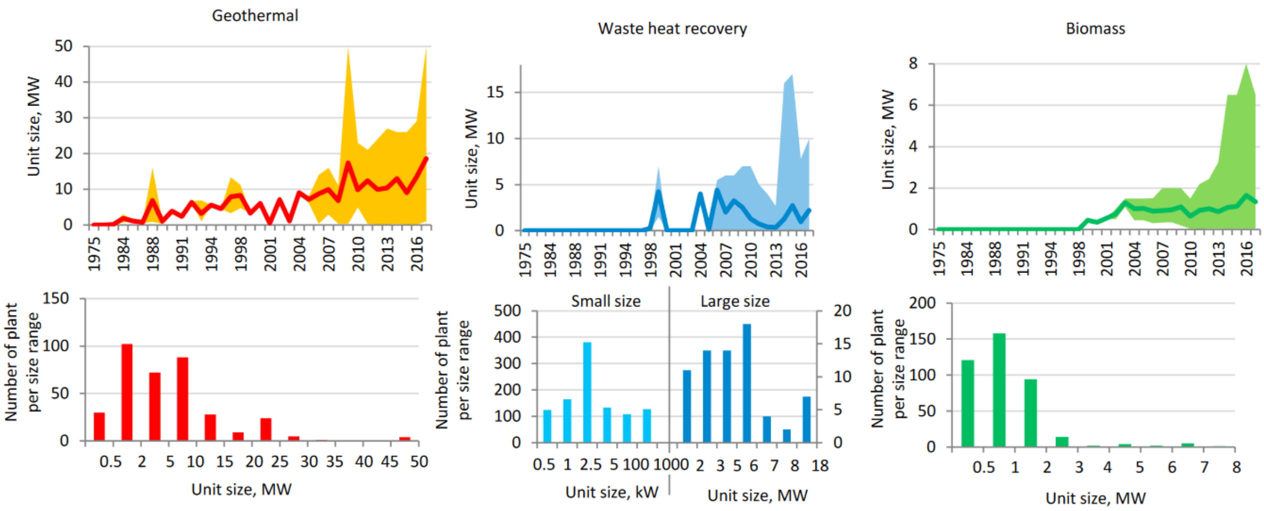

Figure 17: At the top, evolution of ORC unit size divided by application: colored area defines maximum and minimum unit size per year while the line depicts the average installed size. Bar charts at the bottom show the distribution of plants versus the unit size for the three fields considered (Tartière and Astolfi 2017)

Potential for case studies

There is no ORC system available in the project's case studies. Nevertheless, according to technology characterization and the system configuration, possibilities of integration were identified (see Table 15). The biggest potential is visible for industrial sites and those, which are equipped with technologies that may provide a high temperature heat source. For steam turbines, it does not make sense to couple them with ORC system to extract more power; a more meaningful option to increase the flexibility of steam turbine is in fact to change their operation mode from backpressure to condensing one.

Table 15: ORC coupling potential for the analyzed case studies

Case Study	ORC coupling potential *0 - no or small potential* *1 - coupling possible* *2 - coupling recommended*									Waste heat recovery potential *0- no or small* *1- waste heat source available (flue gases etc.)* *2- visible impact on the efficiency after coupling (e.g. with gas engine)* *3- as above, many sources of waste heat (industrial environment)*
	Biomass boiler	Gas boiler	Steam turbine	Gas turbine	Gas engine	Chiller	Heat pump	Electric boiler	Anaerobic digestion	
1 - ME	1		0			0	0			1
2 - PM	1	1	0							2
3 - HO							0	0		0
4 - ACS		1			2		0	0		2
5 - NPT	1		0	2						3
6 - EM		1			2				0	2
7 - PS		1					0			1

4.2.2 Gas-to-Power

4.2.2.1 Gas engines

Flexibility

CHP units based on gas engines are used in commercial, industrial and institutional facilities usually for continuous electricity production, in parallel with the local power grid or in remote areas (island mode operation). Gas engines are fuelled with a wide range of liquid fuels; however the most common fuel is natural gas which allows engines to start quickly. Engines are offered in sizes from 10 kWe to 20 MWe in different variants: electricity only for base-load generation; electricity & heat for cogeneration / combined heat and power; electricity, heat and cooling water for tri-generation /combined heat, power and cooling - CCHP (U.S. Department of Energy 2016, Clarke Energy 2019). Low specific cost of investments (between 770-1 078 EUR/kWth) compared to other technologies (Table 16) make reciprocating gas engines widely used in CHP applications of smaller capacities.

Table 16: Calculated average EU28 specific investment costs for industrial CHP technologies by installed capacity [€/kWth] (Köhler 2017)

	<25 kWth	25-50 kWth	51-250 kWth	251-1000 kWth	1-5 MWth	5-25 MWth	>25 MWth
Steam turbine	n.a	n.a	n.a	1 539	1 509	1 488	1 468
Gas turbine	n.a	n.a	n.a	616	513	431	385
Combined cycle	n.a	n.a	n.a	n.a	n.a	1550	1539
Reciprocating engine	1 078	1 026	924	852	770	n.a	n.a

Reciprocating engines are very well suited to distributed energy applications. Gas engines can be dispatched within minutes, full power achieved in less than 10 minutes compared to 30-45 minutes for combined cycle gas turbines (see Figure 18). Operational ramp rate may achieve up to 50% of nominal power per minute and it can be even 100% for already started engines, which is an outstanding value compared to other technologies. In addition, gas engines may be aggregated into generating sets providing very high flexibility to the whole system, maintaining at the same time their high efficiency. In fact, if there is a need to decrease a power plant load, individual engines are shut down to reduce the overall output of the generating set. Consequently, the remaining engines may generate power at full load, allowing maintaining high efficiency of the system (Wärtsilä n.d.).

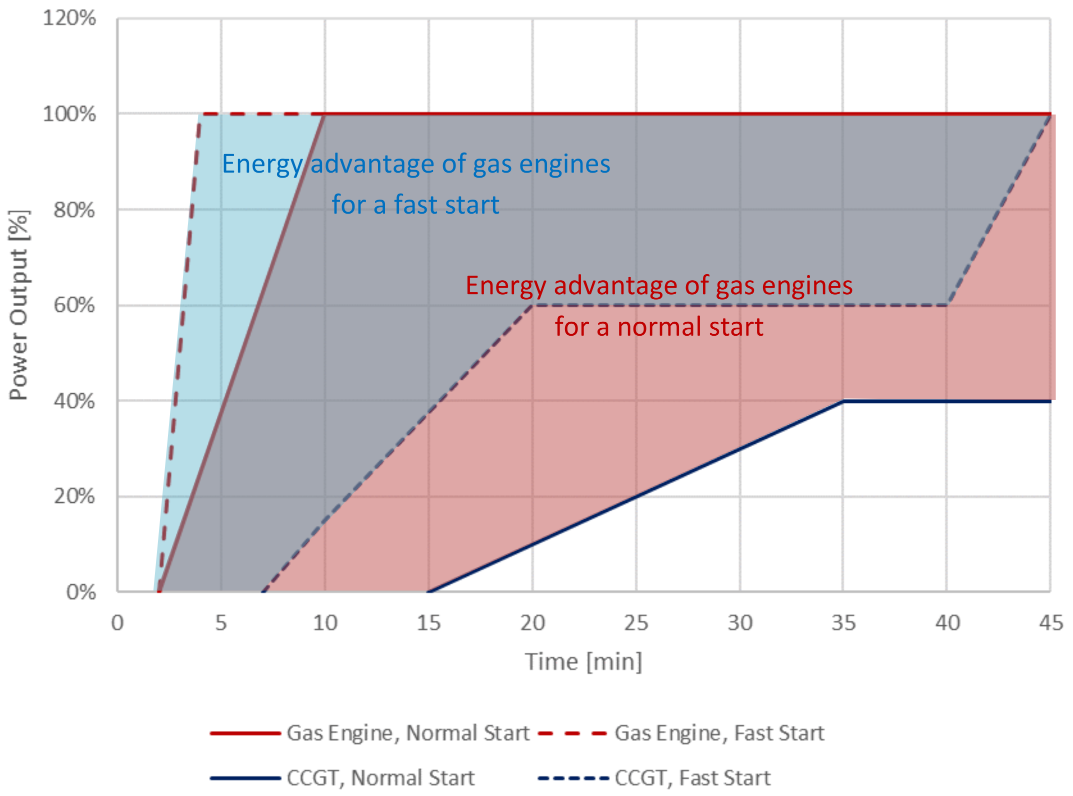

Figure 18: Startup times for gas engines and gas turbines. Own drawing based on (Ralf Grosshauser 2016)

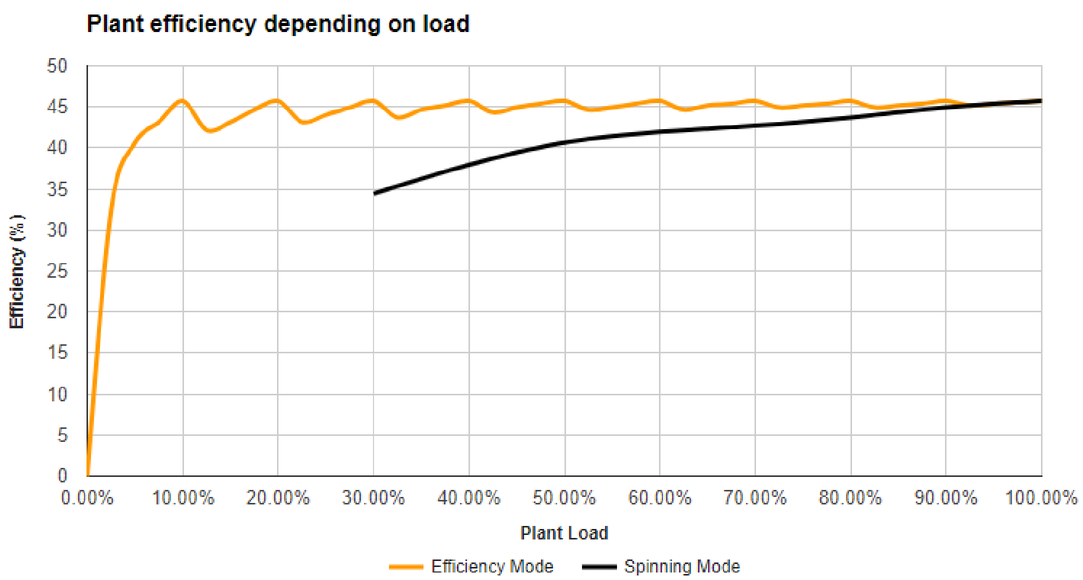

Figure 19: Plant efficiency depending on load, the generating set control mode is represented as an orange curve (Efficiency Mode) (Wärtsilä n.d.)

Table 17: Technology Factsheet- Gas Engine (Wärtsilä n.d., U.S. Department of Energy 2016, Danish Energy Agency 2016)

Parameter	Unit	Value
Power output	MWe	0.1-20
Operating temperature level input	°C	n.a.
Operating temperature level output	°C	365-465
Minimum load	%	30
Controllable range	%	30-100
Net Electrical Efficiency	%	29.6-42
Thermal Efficiency	%	35-53
Cold start up time	min	10-12
Hot start up time	min	0.5-2
Ramp rate up/down	% nom power/ min	20-50 (100 for already started engines)
Specific investment costs	€/kWe	800-1 450

Technical barriers

There are no major technical barriers for gas engines: they do not have minimum load limitations and thanks to the operation of the generating sets, they can maintain high efficiency at partial load. A very high ramp rate may be problematic, especially for large plants that are connected to high voltage grid due to the risk of the transformer overheating during cold start up (Danish Energy Agency 2016). In addition, their use may be problematic due to the CO_2 emission. If they are fuelled with fossil fuels, carbon footprint reaches 450-550 g CO_2/kWh (International Energy Agency 2010), which does not comply with the decarbonisation of the industry (coal-fired units – which are currently being replaced - have CO_2 emission up to 728-990 g CO_2/kWh (M. Steen; Joint Research Centre 2017)).

Expected development

The market for gas engines in Europe will grow in the coming years. The countries of the European Union are committed to the achievement of the targets of the Paris Climate agreement that aims to energy decarbonization and, as a result, significantly accelerates the use of clean energy technologies.

It means that electricity markets will need integrate more and more renewables and very flexible supporting technologies will be needed for peak loads. That is why Europe (including Russia and Turkey) is a global leader when it comes to gas engines installation, with an annual installed capacity addition of approximately 2 GWe in 2017. Gas engines are very mature technology; however, there is still need for further development and increases in achievable power output and efficiency (electric efficiency up to 53%). Gas engines are getting bigger: in recent years the biggest units had around 10 MWe of electrical output, whereas there are currently gas engines of 20 MWe on the market.

In addition, gas engines grouped into generating sets are equivalent to solutions based on combined cycle gas turbines. As a result, gas engines are moving into power ranges typically dominated by turbines (Table 18). It is expected that turbines will remain the preferred solution in large industrial sites with high heat/steam demand and base load power plants, whereas gas engines will take market shares from turbines in district heating networks and peak load power plants. A good example of this market shift is the Stadtwerke Kiel, Germany, where gas engines were explicitly chosen by the customers for feeding the city DH network. The installed CHP is composed of twenty 9.5 MWth gas engines accompanied with a thermal storage (1 600 MWh) and an electrode boiler (35 MWe). The CHP can ramp up from zero to full power in 5 minutes, what is unfeasible for big CCGTs (Power Engineering International 2015, Modern Power Systems 2016, Modern Power Systems 2018).

Table 18: Gas & steam turbines versus gas engines, based on (Modern Power Systems 2018)

Generation type	Power output [MWe]	Gas & steam turbine	Gas engine
District Heating Systems (with CHP)	<25		
	>25		
Industrial Sites (with high heat/steam demand)	<10		
	>10		
Commercial buildings	<3		
	>3		
Power Plants (base load)	<250		
Power Plants (Peaking, i.e. daily cycling/ <2000 hrs per year)	50-200		
Power Plants (Back-up power, i.e. <200 hrs per year)	<50		

* blue bar (as today), red border (2020-2025)

Potential for case studies

Two of the analyzed case studies include gas engines: ACS and EMUASA. ACS uses the gas engines to produce heat that is then delivered to the district heating network and EMUASA uses the gas engines to burn the produced biogas to produce electricity (48% of plant's demand) and heat (100% of plant's demand) for self-consumption.

As for the other technologies, the flexibility of these units is strongly influenced by their system integration and external boundary conditions: ACS is bound to the supply of the district heating demand, EMUASA maximizes self-consumption for the wastewater treatment process. According to a literature review, for ACS, ramp up rates may be expected at the level of 2.52 MWe/min for the 5.04 MWe engine, however the measured value was only about 0.3 MWe per minute. For EMUASA, the ramp-up potential is around 0.5 MWe per minute, assuming that the ramp rate is 50% of nominal power per minute. With these performances, providing services to the electricity grid may require activating back-up engines and additional technologies that will deal with the surplus of heat production (e.g. hot water storage).

Table 19: KCs provided by case study owners for gas engines

Parameter	**Unit**	**ACS** **3 x Gas engine**	**EMUASA** **3 x Gas engine**
Power output	MWe	5.04	0.500
	MWth	4.4	0.519
Net Electrical Efficiency	%	41	n.a.
Net Thermal Efficiency	%	37	n.a.
Cold start up	Min	12	n.a.
Ramp rate up*	% nom power/ min	6 given, 50 based on literature	50 based on literature
Max ramp up potential	MWe/min	0.3-2.52 (literature)	0.25
Total ramp up potential	MWe/min	0.9-7.56	0.5
Comment		Total ramp up potential is given for three running engines. Gas engines operate with the plan to be switched on once per day	Total ramp up potential is given for two running engines, the third one is stand-by

4.2.2.2 Gas turbines

Flexibility

Gas turbines are applied in transport industry (airplanes, ships, trains) or as stationary power generators and direct drives for pumps and compressors.

Gas turbines are available in sizes from about 0.1 to almost 600 MWe, ranging from relatively small micro turbines to very large turbines (open cycle and closed cycle gas turbines) used for power generation in central stations (Figure 20). Big size turbines are split into two groups: heavy-duty gas turbines, dedicated mainly to power & utility applications, and aero-derivative turbines, which are a lighter weight version of a gas turbine firstly used as aviation engines. For CHP applications, gas turbines typically have sizes greater than 5 MWe and they provide high temperature exhaust gases that can be used either to generate high-pressure steam, hot water or chilled water when it is coupled with an absorption chiller. Hot gases can be also used directly in industrial applications for heating or drying (U.S. Department of Energy 2016).

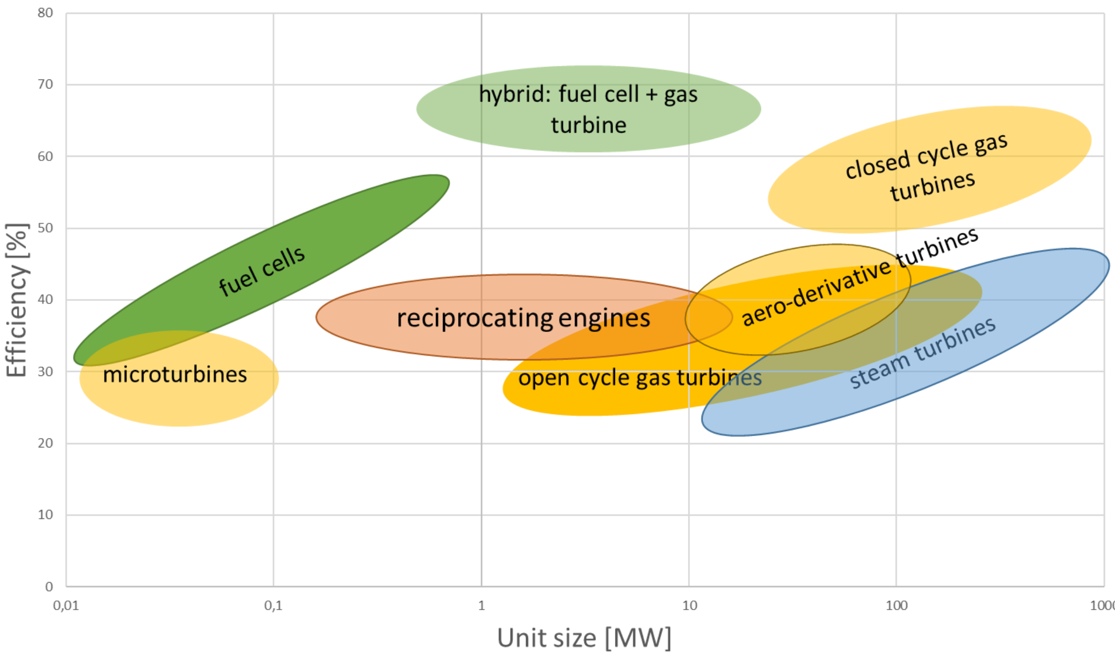

Figure 20: Size of gas turbines and their efficiency. Own drawing based on data and figures from (M. Steen; Joint Research Centre 2017)

The electrical generation efficiency of gas turbines varies between 25 and 62.22% (GE Power 2016); very high efficiencies are achieved for combined cycle gas turbines (gas turbine and steam turbine). Nevertheless, the efficiency is highly impacted by partial load operation, declining as the load decreases (see Figure 21). In addition, the load affects not only the efficiency but also the emissions, which increase when lowering the power output. This technical constraint is defined as the minimum environmental load (the minimum emissions-compliant load), which is the lowest output at which environmental limits for nitrous oxides (NOx) and carbon monoxide (CO) emissions are met. This load is around 50-60% for CCGT heavy-duty turbines (even if, by optimizing the system, it can be reduced to 30-40% (Dr. Artur Ulbrich 2016)), around 25-40% for simple cycle turbines and 5-18% for aero-derivative turbines. For hot start conditions, the start-up time for combined cycle gas turbine is about 30-45 minutes, for simple cycles it is about 10-15 minutes and less than 5 minutes for aero-derivative units. Ramping rates can reach up to 6%/min for CCGT; 7.5-16.3%/min for SCGT (see Figure 22) and 40-132%/min for the aero-derivative turbines (Mike Welch 2016, Miguel Angel 2018).

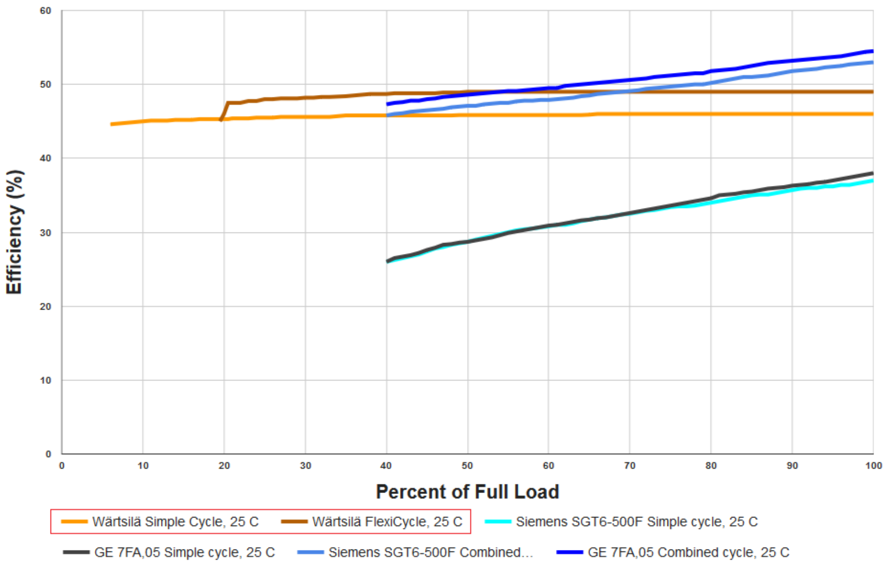

Figure 21: Partial load efficiency of gas turbines and gas engines (in a red box) (Wärtsilä n.d.)

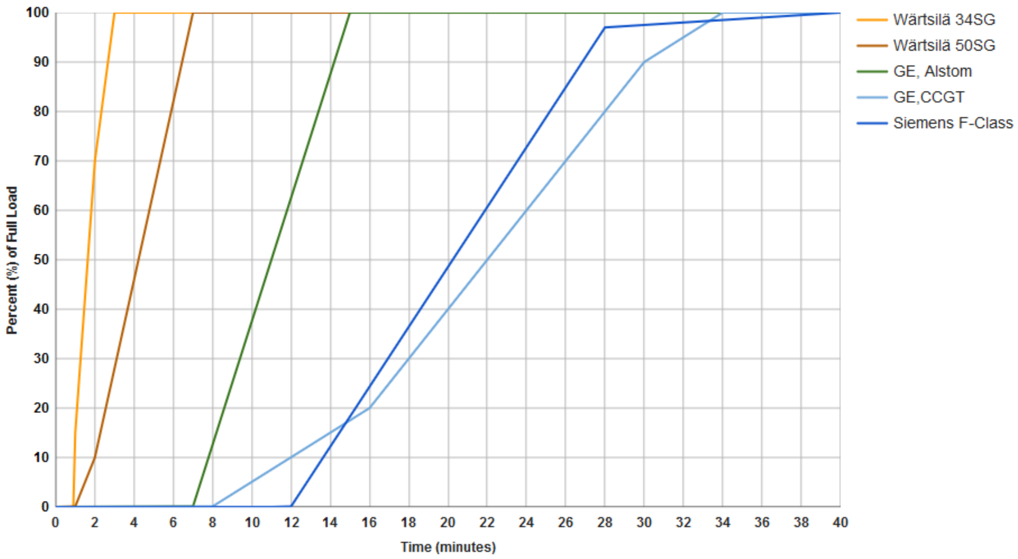

Figure 22: Start up times for hot conditions, Wärtsilä- gas engine; GE, Alstom- simple cycle; GE, CCGT and Siemens F-Class-CCGT (Wärtsilä n.d.)

Table 20: Technology Factsheet- Gas Turbine (Wärtsilä n.d., U.S. Department of Energy 2016, Miguel Angel 2018, Craig S. Brooker 2017, Danish Energy Agency 2016, Green 2017, GE Power 2019, Energy Technology Systems Analysis Programme 2010)

Parameter	Unit	Simple cycle combustion heavy & duty turbine	Simple cycle Aero-derivative	Combined cycle combustion turbine
Power output	MWe	3-593	36-117	44-593
Operating temperature level input	°C	n.a.		

Parameter	Unit	Simple cycle combustion heavy & duty turbine	Simple cycle Aero-derivative	Combined cycle combustion turbine
Operating temperature level output	°C	365-465	430-530	Hot water or steam depending on the pressure
Minimum load	%	25-40	5-18	30-60
Controllable range	%	25/40-100	5/18-100	30/60-100
Net Electric Efficiency	%	23-40	32-42	52-62
Thermal Efficiency	%	44-50	44-50	33-38
Cold start up time	min	10-45	10-12	145-255
Hot start up time	min	5-15	5	30-45
Ramp rate up/down	% nom power/ min	7.5-16.3	82-132	5.2-6
Specific investment costs	€/kWe	1 130 for 50 MWe 680 for 100 MWe 435 for 280 MWe 375 for 370 MWe	960 for > 100 MWe 1 330 for 50 MWe	545 (400 MW, F-class) 595 (600 MW, H class)

Technical barriers

A major limitation is the minimum environmental load that bounds controllable ranges for gas turbines (see Table 20). Due to this fact, heavy-duty CCGTs shall be used mainly for base load applications. In addition, fluctuating loads and an increased number of start-ups will reduce lifetime of gas turbines, thus resulting in higher maintenance costs (see Figure 23).

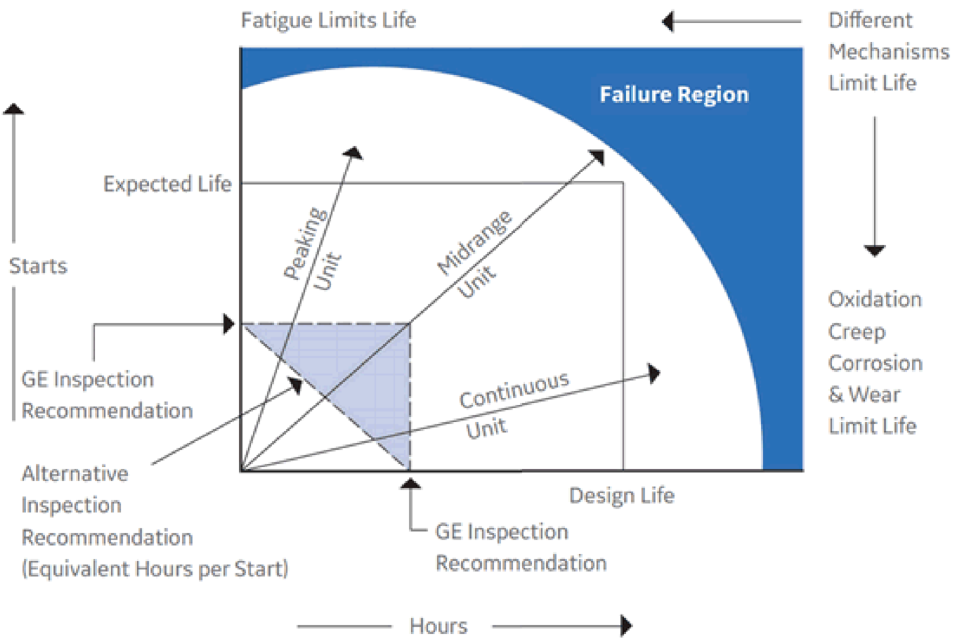

Figure 23: Influence of flexible operation of gas turbines on their lifetime (Eggart, et al. 2017)

Expected development

Technical development

From a technical point of view, ongoing research and development aim at achieving the efficiency and flexibility that will be required by the energy transition. Manufacturers have developed recently gas turbines with electric efficiency reaching 62-64%, and are on track to achieve 65% efficiency by 2020s with a ramp up rate of 7.5%/min for CCGT units. For aero-derivative turbines, ongoing research is conducted in order to shorten start-up times: recently a mobile 44 MWe unit was presented, which is able to start up and achieve full load within less than 8 minutes and needs only two weeks to be installed on site (D. Proctor, POWER 2018).

Market development

Wind and solar energies are by far the biggest competitor to medium and large size gas turbines. Projections for global net electricity production by fuel indicate that natural gas will remain a major long-term player in the field of electricity, with expected annual growth by 1.4% over the next ten years. However, in the same period the share of renewable energy sources is expected to increase by 3.1% annually. This increasing role of renewables has a big impact on the use of gas turbines and consequently on the number of orders for new gas turbines (see. Figure 24). Small sized GTs (up to 20 MWe) are competing with gas engines (see Section 4.2.2.1), thus leading energy sector in the direction of distributed energy based on multi generating sets (Drew 2018).

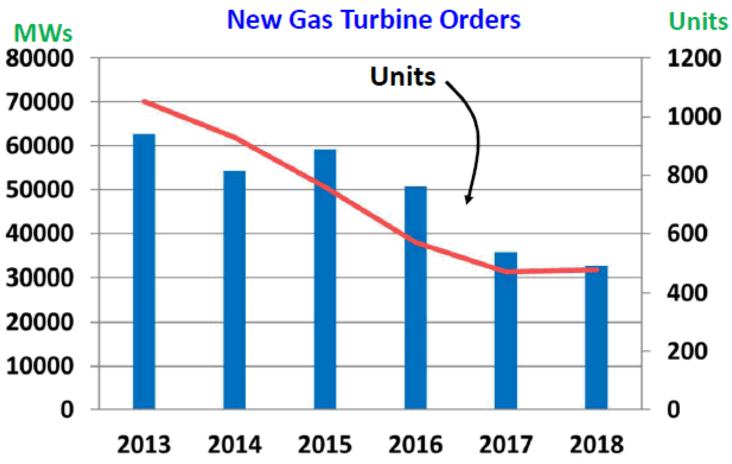

Figure 24: Gas turbines worldwide orders 2018 (Brough 2019)

This trend is visible in the United Kingdom where natural gas plays a key role and the combined cycle gas turbine (CCGT) is the major technology that uses gas for power generation, with an installed capacity of 32 887 MWe in 2017 (40.5% of the total capacity of the UK (Department for Business, Energy & Industrial Strategy 2018)). However, the most recent projections published by the UK Department for Business, Energy and Industrial Strategy (BEIS) in 2017 show that this lead is going to change. They forecast only 6 GWe of new gas capacity to be built by 2035, which represents a significant scaling back from the 14 GWe by 2035 expected in 2016 and 25 GWe seen in the 2015 projections. This negative trend is mainly caused by the unexpected speed of the cost decrease of renewables and batteries. The increasing operability of electric power systems able to better integrate intermittent renewables and the increasing gas prices are also relevant factors (Evans 2018). As a result, the gas-based generation is expected to keep decreasing, from close to 160 TWh in 2017, to around 80 TWh in 2025, to even below 60 TWh after 2035 (Department for Business, Energy & Industrial Strategy 2018). Nevertheless, gas turbines may still increase their presence mainly in currently coal-based countries such as China and India, where they replace deployed and less environmentally friendly coal-fired units (GE Power 2018).

Potential for case studies

Gas turbines are available in the NPT case study: in the Baglan Power Plant there is a 520 MWe CCGT unit and a smaller aero-derivative turbine that provides black start capability (Power Technology 2003). According to calculated values, Baglan Power Plant should be able to ramp up/down at the rate of 56.8 MWe/min.

Table 21: KCs provided by case study owners for gas turbines

Parameter	Unit	Neath Port Talbot	
		Baglan Power Plant	
		CCGT	aero-derivative gas turbine
Power output	MWe	520 (480 GT + 40 ST)	32
Ramp rate up *(calculated values)*	% nom power/ min	6	80
Max ramp up potential	MWe/min	31.2	25.6
Total ramp up potential	MWe/min	56.8	
Main fuel		Natural gas	

4.3 Supporting technologies

4.3.1 Thermal Energy Storage

In Multi-Energy Systems, electricity production and consumption are often coupled with the supply of heat, e.g. cogeneration via CHP units or P2H via HPs. The coupled production is usually driven by customer heat needs, which lowers the degrees of freedom for variable electricity production. Therefore, a flexibility increase on the electricity side requires the decoupling of the heat demand from heat supply of cogeneration and P2H units. Thermal Energy Storage (TES) enables this decoupling, e.g. electricity production from CHP units can be increased if heat surplus is stored; vice versa, CHP electricity production can be decreased if the related heat demand is covered by previously stored heat (or alternative heat sources, see Section 4.2). For electricity consumption in P2H units, similar considerations arise.

Nevertheless, heat storage provides no direct flexibility to the electrical grid, but indirect one by enabling other technologies to operate more flexibly.

In relation to the MAGNITUDE case studies and objectives, storage of hot water in tanks for DH as well as steam storage for industrial process heating are the most promising technologies. Seasonal thermal storage in aquifers or pits is not in the scope of MAGNITUDE, since it plays a role mainly in heating systems with solar heat production, with no or just a low effect on the power system.

4.3.1.1 Thermal storage - hot water tanks

Flexibility

Thermal storage via large hot water tanks is mainly used in DH networks and it enables the decoupling of power and heat production for CHPs, HPs and electrical boilers. Small tanks are used at the building level for daily peak demands of domestic hot water and heat. Therefore, hot water tank sizes range from some 100 dm^3 for single buildings to 50 000 m^3 for large DH networks. The corresponding capacities in MWh depend on the temperature differences and on the temperature levels of the entire heating system. Typically, the sizing is done to provide the maximum heat demand for at least some hours to several days (Danish Energy Agency 2018). In (Prognos 2011), a range of 30-50% of the heat peak load as the optimum storage size is estimated. Therefore, capacities in terms of stored energy can achieve more than 2 000 MWh in large DH networks.

Three types of hot water tanks are widely used, distinguished mainly by the pressure - and corresponding temperature - level: atmospheric ones with 98 °C, two-zone ones with 120 °C and pressurized ones with 130°C. Around 45 kWh/m^3 of useful heat can be stored in atmospheric tanks and up to 70 kWh/m^3 for pressurized ones.

Hot water tanks consist of stainless steel vessels, insulation and connecting pipes and valves to the heat source and sink. There is a strong scale effect on the CAPEX (VDE 2015): for large-scale tanks, the investment costs for tanks are about 50-100 €/m^3 (resp. 0.5-3 €/kWh), which increase for smaller ones for buildings to several hundreds of €/m^3 (Sterner 2017). The costs are also varying due to system integration.

The efficiency corresponds to heat losses over time, and depends mainly on the thickness of the insulation. Larger tanks are more efficient thanks to the better surface-to-volume ratio. Mean values for the specific heat loss are around 10 W/m^2, or about 0.2% of capacity per day.

Table 22: Technology Factsheet - Hot water tanks

Parameter	Unit	Value
Heat storage size	m^3	0.1-75 000
Heat storage capacity	MWh	0.01-2 500
Operating temperature level input	°C	30-98
Operating temperature level output	°C	40-99 (atmospheric pressure) <150 (pressurized)
Minimum load	%	0
Controllable range	%	0-100
Thermal Storage Efficiency	%	95-99
Start up time	Min	0
Specific investment costs	€/m^3 (€/kWh)	50-600 (5-20)

Technical barriers

There are no technical barriers preventing the diffusion of this technology: hot water tanks are a well-proven and widely used and established technology, as well as economically competitive (DNV GL and CE Delft 2015). However, integration into a district heating system can be very complex and costly, due to different pressure and temperature levels, flow parameters or space restrictions (VDE 2015). Corrosion risk is unavoidable in every water-containing system like DH pipes or water storage tanks. Corrosion can lead to unexpected leakage, increase of the maintenance costs as well as decrease of the storage efficiency. Furthermore, corrosion is temperature dependent: the higher the water temperature, the faster corrosion proceeds. Therefore, this has crucial implications for hot water storage, in particular for high temperature storage. To minimize corrosion problems inside water tanks, the same solutions as for DH networks are applied: e.g. oxygen-free atmospheres due to N_2 usage as inert gas, low pH values of the utilized water (water preparation needed) or sacrificial anodes. The capacity of large tanks complies with the requirements of grid services provision, whereas the small ones are only exploitable via aggregation.

Expected development

For the future, no major improvements for hot water tanks are envisaged (Sterner 2017). Nevertheless, costs and heat loss decreases are still the field of ongoing developments, achievable for example by innovative arrangements of temperature layers within a tank. Another development subject is motivated by the shift of heat production from CHPs to HPs and the related lower temperatures achievable for heat provision; however, the lower the temperature of stored water, the lower the storage capacities within the same volume (Danish Energy Agency 2018). On the other hand, large tanks are conceived to act as seasonal storage of heat, at least for small DH networks.

Thermal storage is about 100 times cheaper than electricity; therefore, it is clear that with increasing RES in the electricity mix, the use of TES will also grow. In this regard, in (DNV GL and CE Delft 2015) heat buffering is considered as a key technology for hybrid heating systems. (Prognos 2011) estimates only for Germany a potential of 100 GWh for hot water storage in large DH systems.

Potential for case studies

Large hot water tanks are installed in the ACS and in the Mälarenergi case studies, whereas at HOFOR small water tanks are implemented, in the houses for domestic hot water demand and at the booster-HP-level as accumulator tanks. The main purpose of such a configuration is electricity load shifting via electric water heaters and the corresponding hot water tank, combined with district heating network, the sizing of the hot water tank being the crucial parameter. For Paris-Saclay, the same configuration is considered as an improvement option.

The corresponding KCs are given in Table 23.

Table 23: KCs provided by case study owners for hot water tanks

Parameter	Unit	ACS	Mälar-energi	Mälar-energi	HOFOR (single house)	HOFOR (Booster HP)	HOFOR (Cruise terminal)
Heat storage size	m^3	2x1 200	25 000	26 000	0.092	2	274
Heat storage capacity	MWh	2x35	900	1 200	0.003	0.06	4
Operating temperature level input	°C	60	40	n.a.	20	n.a.	20
Operating temperature level output	°C	95	100	n.a.	60	n.a.	95
Flexibility potential*	h	8	5	5	n.a.	n.a.	n.a.

*The flexibility potential is calculated as the time during which the installed heat storage can take over the heat provision of the coupled production technologies (gas CHP for ACS ; biomass boiler 5/6 for Mälarenergi).

4.3.1.2 Thermal storage - steam accumulators

Flexibility

Steam accumulators are used in industrial steam networks, usually to cover steam peak demands in batch processes, and as a back-up system instead of auxiliary boilers (Spirax Sarco 2016). In such industrial processes, steam has to be delivered with constant quality within some minutes for at least 15 minutes.

If the dimensioning of the steam accumulator and the CHP unit producing steam is appropriate, steam storage can – similarly to hot water tanks - contribute to the decoupling of power production and steam demand. The storage capacities are usually in the range of several MWh, but new developments are broadening the capacities into the GWh range by cascading or several storage units (EnergyNest n.d.). The costs of steam storage highly depend on the chosen technology (25-120 €/kWh according to (Seitz 2017)).

The working principle of a steam accumulator is quite simple. A storage tank is largely filled with boiling water. The remaining space above the water is filled with steam at the same temperature. If steam is released, post-evaporation begins, and pressure and temperature drop. Once the minimum discharge pressure has been reached, heat must be further reinjected into the steam accumulator.

The working range of the steam accumulator is defined by the initial and final steam parameters (pressure and temperature) as well as by the initial degree of filling with boiling water. The key storage parameter is the ratio between the amount of steam that can be extracted and the storage volume.

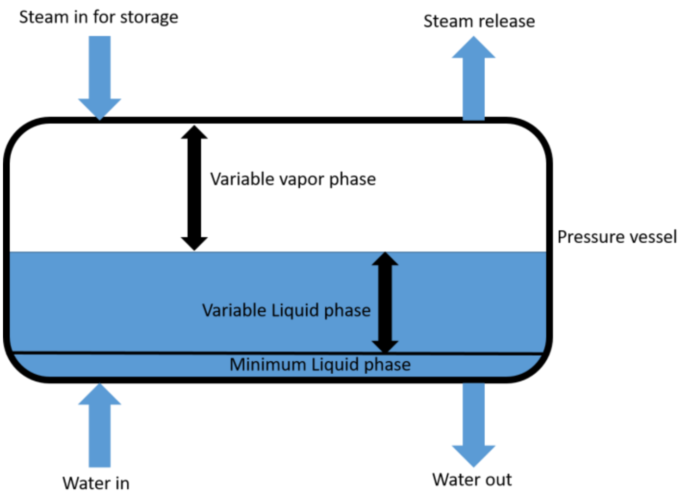

Figure 25: Steam accumulator scheme (Ruths-storage)

Table 24: Technology Fact sheet - Steam accumulator

Parameter	Unit	Value
Heat storage capacity	MWh	1-1 000
Operating temperature level input	°C	200-350
Operating temperature level output	°C	200-350
Minimum load	%	0
Controllable range	%	10-100
Thermal Storage Efficiency	%	95-99
Start up time	Min	< 0.5
Specific investment costs	€/kWh	25-120

Technical barriers

The engineering requirements to integrate steam accumulators are much higher than for hot water tanks, not only due to temperature and pressure levels (above 300 °C and 25 bars), but also due to the fast response times of a few minutes and the required quality of the provided steam for durations up to 30 minutes. The input pressure during charging has to be higher than the output pressure at discharging. The outlet steam parameters are slightly decreasing during discharging; so, steam quality is not constant and this fact needs to be compensated by process design's optimisation. Concerning using steam storage for flexibility provision, the main purpose within the industrial steam network is the provision of steam for the production process, which lowers the degree of freedom of CHP production significantly.

Expected development

Steam accumulators are an established technology, but with significant potential for performance improvements. In the near future, the construction costs will decrease, due to improved heat transfer concepts (Sterner 2017). Another development within the next decade will be the storage of heat at temperatures between 300 °C and 1 000 °C. Besides the direct storage of steam in pressurized vessels, new concepts of steam provision are under investigation: ongoing research and development aim at using and improving new materials, like molten salts from solar power plants, thermo-oils or cements (BINE Informationsdienst 2018). Their main advantage is a significantly higher energy-density due to increased storage temperatures; however, the extraction of the heat at the required temperatures and pressures remains difficult. Nevertheless, these potential, developments and business opportunities are seen as very promising and boosted by the high heat demand of industries.

Potential for case study

The only case study with a steam accumulator is the Austrian paper mill.

Table 25 summarizes the calculated characteristics of this accumulator, since there are no disclosable information on its sizing.

Taking into account the thermal output coming from the installed steam turbines (27-52 MWth) that are connected to the steam accumulator, it can be calculated that a steam storage would not provide a big potential for flexibility if used only as a steam "holder". Based on steam properties and the storage's volume, it can be calculated that its holding capacity is around 0.58 MWth. The result is different if the storage is operated more as a buffer tank, connected to heat exchangers that provide heat do a district heating network. In this configuration it would be able to deal with up to 32 MWth within one hour. This example shows how the effectiveness of such a storage relies on its integration in the steam network's architecture.

Table 25: Steam accumulator coupling potential for the Austrian paper mill

Parameter	Unit	Value
Heat storage capacity	m^3	350
Heat storage capacity	MWth	0.58
Operating pressure level input	bar	3.5
Operating temperature level input	°C	190-210
Operating temperature level output	°C	n.a.

4.3.2 Gas storage & Upgrading

Flexibility

As mentioned in the previous paragraphs, electricity production and consumption are often coupled with heat supply. Alternative heat-only sources can cover heat demand and enable to reduce the power production to avoid curtailment of renewable electricity. For this, gas-fueled units are the most appropriate technology, thanks to their fast start-up times (see Section 4.2.2). Their functioning requires either a gas grid connection or an intermediate gas storage, in particular for biogas production sites like Waste Water Treatment Plants (WWTP), biowastes and agricultural Anaerobic Digesters (ADs). For the latter ones, upgrading of surplus of biogas and storing into the gas grid can also be an alternative. Nevertheless, as for thermal storage, gas storage and upgrading provides no direct flexibility to the electrical grid, but indirect flexibility.

Technical barriers

Gas storage is a well-proven and established technology since more than 100 years, with external or underground storage of different capacities (up to 4 billion Nm^3 for caverns) and pressure ranges (from one up to hundreds bars). The connecting pipes determine the input and output flow, and so the technical KCs like minimum/maximum loads, capacities and ramp up/down times. The gas production or consumption rates are usually the determinant factors for the sizing.

For the upgrading of biogas to natural gas quality and injection into the gas grid, several technologies are available at Technology Readiness Level (TRL) 9. However, the legislative and technical requirements are slightly different in the different European countries for the national gas grid providers.

The costs for gas storage as well as for upgrading are currently the main barrier to the wider diffusion of these technologies. CAPEX is ranging from 12-65 €/Nm^3 for aboveground gas storage, which is the appropriate solution for biogas producing facilities like WWTPs, biowastes or agricultural ADs. The OPEX are negligible.

Much more expensive is the upgrading of biogas to Natural Gas (NG) quality. The upgrading costs are about 1.5 ct/kWh based on the Higher Heating Value (HHV) of the gas, which have to be added to the biogas production costs to quantify the benefits of providing flexibility by this mean.

Expected development

Due to the Ukraine crisis in 2014, Europe has increased its gas storage capacities over the last years. Nevertheless, the future development highly depends on geopolitical developments, as well as the development of Power-to-Gas (P2G). In fact, P2G requires intermediate gas storage, either directly on the production site of the Synthetic Natural Gas or in the existing gas network. For Germany, the rollout of P2G is not expected before 2035 (Maier 2018). On the other hand, developments in automotive industry will also lead to an increase of gas storage facilities, since either Liquefied Petroleum Gas (LPG), Compressed Natural Gas (CNG) or hydrogen are used as fuels. The amount of gas fueling stations has been stable over the last decade.

Upgrading of biogas to natural gas quality is expected to grow within the next decade for two reasons. Firstly, biogas can be stored in the grid after upgrading. Therefore, the biogas can be converted into electricity if no or low renewable electricity is produced ("dark doldrums"), in good accordance with the expected increase of variable RES. Furthermore, the strong demand in the mobility sector to decrease CO_2

and other emissions will lead to a larger share of renewable fuels; partly derived from upgraded biogas. Therefore, a cost decrease is expected (Bothe 2017).

Potential for case studies

In the EMUASA case study, a spherical gas storage stores biogas coming from anaerobic digesters. According to a volume of the gas storage in EMUASA at the level of 2 700 m^3 and biogas composition (ca. 65% CH_4 and the rest CO_2), it can be calculated that the storage potential is around 17 MWh, which corresponds to 17 working hours of the gas engines available on site operated at the full load. However for EMUASA, as for any WWTP, the main bottleneck to flexibility provision is the plant's high electricity demand, so that the entirety of the electricity produced by the engines is required for self-consumption. Therefore, no surplus of biogas may be available in WWTPs, and the provision of flexibility to the electrical grid may not be feasible. To overcome this obstacle, new concepts for WWTPs are under development, e.g. the co-digestion of organic wastes to increase the biogas production, the increase of methane produced via P2G concepts or the decrease of the electricity consumption for the waste water treatment (e.g. sludge treatment pumps).

4.3.3 Heat-to-Cold: sorption chillers

Flexibility

From a technological point of view, there are two different working principles: absorption and adsorption. In both cases they are based on one pair of refrigerant and one pair of sorbent. In the case of absorption, the refrigerant is absorbed, i.e. dissolved in the sorption liquid, while in the case of adsorption chillers it is only adsorbed on a solid sorbent. Sorption chillers have the same working cycle as compressor chillers, they are also composed of evaporator and condenser, but instead of a compressor and a prime mover, they are equipped with a thermal compressor system consisting of an ab/adsorber, a solution pump (only for absorbers), and a generator (see Figure 26). The cycle is thermally driven and an external heat source is used for regeneration of an absorption solution. In a low-pressure system, an absorption liquid is evaporated, which extracts heat from the chilled water.

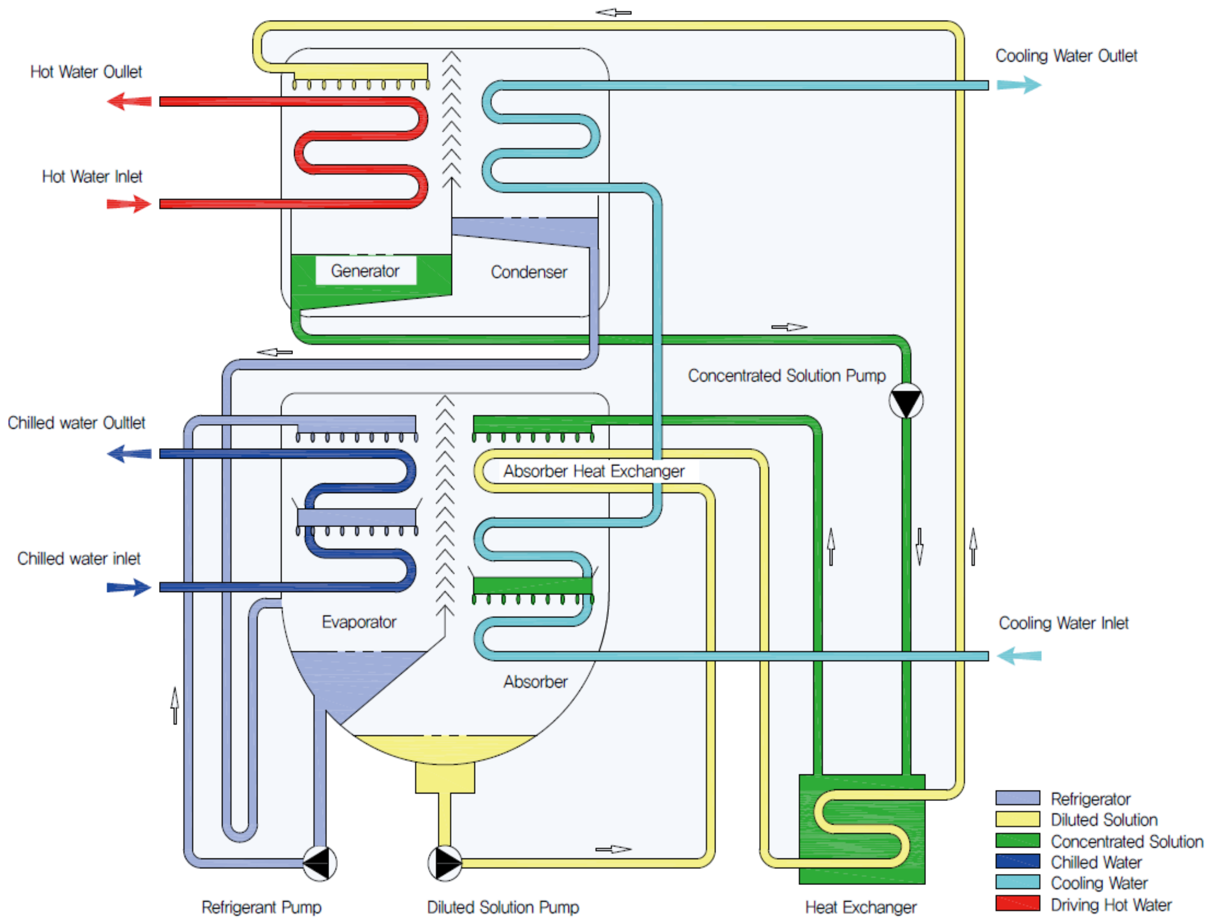

Figure 26: Single effect hot water driven absorption chiller (Goldman Energy 2016)

Thermal energy can be supplied either directly by direct firing or indirectly to the chiller. External sources include low and high temperature hot water, steam or combustion exhaust.

Absorption chillers mainly use two combinations of refrigerant and absorbent: water/lithium bromide and ammonia/water (refrigerant/absorbent). LiBr sorption chillers with a capacity ranging from 15 to 14 000 kW are limited by operating temperatures (min. 3-4 °C) and thus are used in air-conditioning systems or in a district cooling networks. On the other hand, ammonia chillers with a power output of 18-700 kW, in which water is the absorbent, are mainly used in industrial systems, where temperatures down to -60 °C are required (U.S. Department of Energy 2017). The COP for absorption chillers is between 0.5 up to 1.3 depending on the temperature of the external heat source, number of stages and used solution.

Adsorption chillers have lower thermodynamic efficiency but, compared to absorption devices, they can be sourced with lower temperatures. This technology may be interesting for coupling with low-temperature district heating network or solar energy (European Technology Platform on Renewable Heating and Cooling 2012).

Indirect sourcing of sorption chillers is their big advantage when they are coupled with a CHP, as it allows managing the surplus of heat production resulting in maximum utilization of the CHP during a summer season. Although sorption chillers do not provide flexibility to the electricity system in an active way, they can increase the flexibility of the generating units coupled with them. In order maximize the synergies between the heat source and absorption units, the installation of thermal storage may be needed, both for heat (e.g. steam, water accumulator) and cold (ice storage, chilled water tank) storage.

Table 26: Technology Factsheet- Absorption chiller (Große, et al. 2017, Johnson Controls 2018, U.S. Department of Energy 2017, SUMMERHEAT 2009, Bakker, et al. 2013)

Parameter	Unit	Adsorption		Absorption		
		water silica gel	water zeolite	single stage water/ LiBr	double stage water/ LiBr	ammonia/ water
Power output (cold output)	kW	7.5-500	9-430	15 – 14 000	200 – 6 000	18 – 700
Operating temperature level input	°C	60-90	45-95	75 – 110	135 – 200	100 – 180
Operating temperature level output	°C	3-4	3-4	3-4	3-4	-60
Minimum load	%	n.a.	n.a.	10		
Controllable range	%	n.a.	n.a.	10-100		
COP Cooling	-	0.5-0.7	0.5-0.6	0.6-0.8	0.9-1.42	0.5-0.7
Cold start up time	Min	n.a.	n.a.	30		
Hot start up time	Min	n.a.	n.a.	0		
Ramp rate up/down	% nom power/min	n.a.				
Specific investment costs*	EUR/kW	350-1 500		1 501 for 176 kW 576 for 1 547 kW 450 for 4 642 kW	751-826 for 1 161 kW 500-550 for > 3 517 kW	

Technical barriers

Besides problems such as crystallization of the sorbent and corrosion and efficiency losses from the circulation pumps for absorption chillers, there is no more major material problems. However, the efficiency of adsorption chillers is highly dependent on the outdoor temperature when the cooling towers are cooled down with the air, which is not as much visible for compressor type chillers (see Figure 27 and Figure 28). The COP of the compressor type reaches a value of 4.49 when outside temperature is 25 °C, whilst for adsorption unit it reaches only 0.14 and drops down to 0 when outdoor temperature is being around 30 °C (Grzebielec, et al. 2015). A similar behaviour may be observed for the absorption devices.

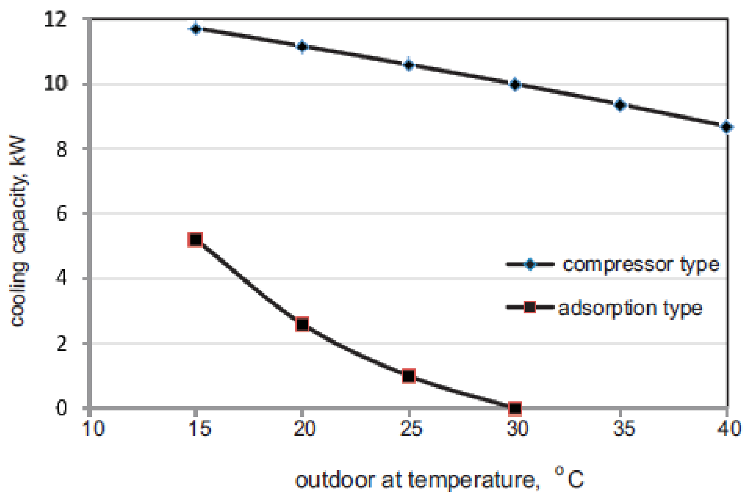

Figure 27: Cooling capacity for different device types (Grzebielec, et al. 2015)

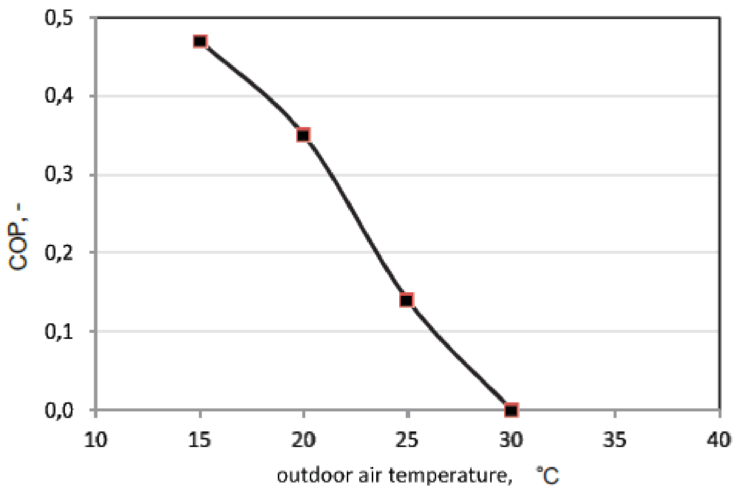

Figure 28: Coefficient of performance for adsorption refrigeration unit (Grzebielec, et al. 2015)

Expected development

Absorption chillers are considered a mature technology and high-quality products offered by many manufacturers already exist on the market. Therefore, from a technological point of view, there are three main technological fields to develop: combined and multi-stage thermodynamic cycles, mobile application and building-integrated sorption systems. On the other hand, solid adsorption devices have been less investigated and require further development. Research groups for adsorption systems focus mainly on fundamental activities as materials research, etc., concerning heat transfer intensification, improved cycles and so on. From a market point of view it is expected that absorption systems will penetrate the market more and more (mainly thanks to thermally-driven heat pumps capable to provide heat and cold), whilst adsorption systems may be negligible if there is no technological breakthrough (European Technology Platform on Renewable Heating and Cooling 2012).

Potential for case studies

In the project's case studies, cold is provided by means of heat pumps and only in Mälarenergi there is a dedicated absorption chiller. The main idea behind having sorption chillers is to provide an additional commodity (cold) to clients and either maintaining the optimum load of coupled heat generators or using low-cost heat sources (waste heat, renewables) in the most efficient way. Other case studies can be equipped with sorption chillers but the decision should be taken according to the local clients' needs.

Table 27: Sorption devices installed in the case studies

Case study	Absorption chillers		Heat pumps		
	Ouput MWth	Input MWth	MWth Heat	MWth Cold	MWe
Mälarenergi AB	7	9	27	22	9.0
ACS	/	/	18	13.7	6
Paris Saclay	/	/	15	10	5

5 Analysis of technology flexibility potential

In this paragraph, the flexibility potential of the technologies, described in Section 4, is associated to the requirements for the provision of the flexibility services identified in D3.1 (Cauret, et al. 2019).

First, the characteristics of the services to the electricity grid and associated products are summarised and their requirements which need to be satisfied by the technology response are highlighted.

The capability of sector coupling technologies to provide the services is then evaluated, based on the results of the previous analysis. The current technological bottlenecks which limit the provision of flexibility services and the correspondent expected development are then summarised.

5.1 Characteristics of services identified in D3.1

The following criteria have been applied in Deliverable D3.1 (Cauret, et al. 2019) to select the most relevant services to be provided by Multi Energy Systems to the electricity grid:

- Services allowing to increase the share of Renewable Energy Sources (RES), avoid curtailment of variable RES and enhance the security of supply;
- For which synergies between gas, heating/cooling and electricity systems provide real opportunities;
- Showing a potential value for the provision by Multi Energy Systems based on the data collected so far (technical, regulatory and market design).

Targeting the above-mentioned criteria, the following services have been selected to be further studied in the project, since they address specific needs of the electricity sector.

Table 28: Needs of the electricity sector and services identified in D3.1.

Needs	Services	Short description
Frequency control and balancing	***FCR (Frequency Containment Reserve)***	Activated to stop a frequency deviation after the occurrence of an imbalance on the European synchronous network.
	aFRR (automatic Frequency Restoration Reserve)	Active power reserve, which is automatically activated to replace the FCR after a frequency deviation and to restore the frequency to its nominal value.
	mFRR (manual Frequency Restoration Reserve)	Active power reserve which is manually activated after a frequency deviation to complement or to release the aFRR if the demand for secondary control reserve is too high.
	RR (Replacement Reserve)	To provide an active power reserve which is manually activated to progressively restore the activated FRR and/or support FRR activation.
Energy trades	***Day ahead energy trades/market***	Trading of electricity for the following day. Biggest market volume.
	Intraday energy trades/market	To trade on the short term energy volumes to be sold/purchased. Traded volumes currently increasing because of the development of intermittent energy generation.
System adequacy	***Capacity requirement mechanisms***	To contribute to the security of supply, avoid or postpone the unexpected accelerated shutdown of old conventional plants and compensate prolonged outages of crucial assets. Currently existing under very different forms in GB, FR, ES, SE and soon in IT*.
Congestion management	***Re-dispatching mechanisms or active power control***	Measures taken when the forecasted or the real power flows exceed the physical capability of the grid components.

* AT: Austria, DK: Denmark, FR: France, IT: Italy, ES: Spain, SE: Sweden, GB: Great Britain

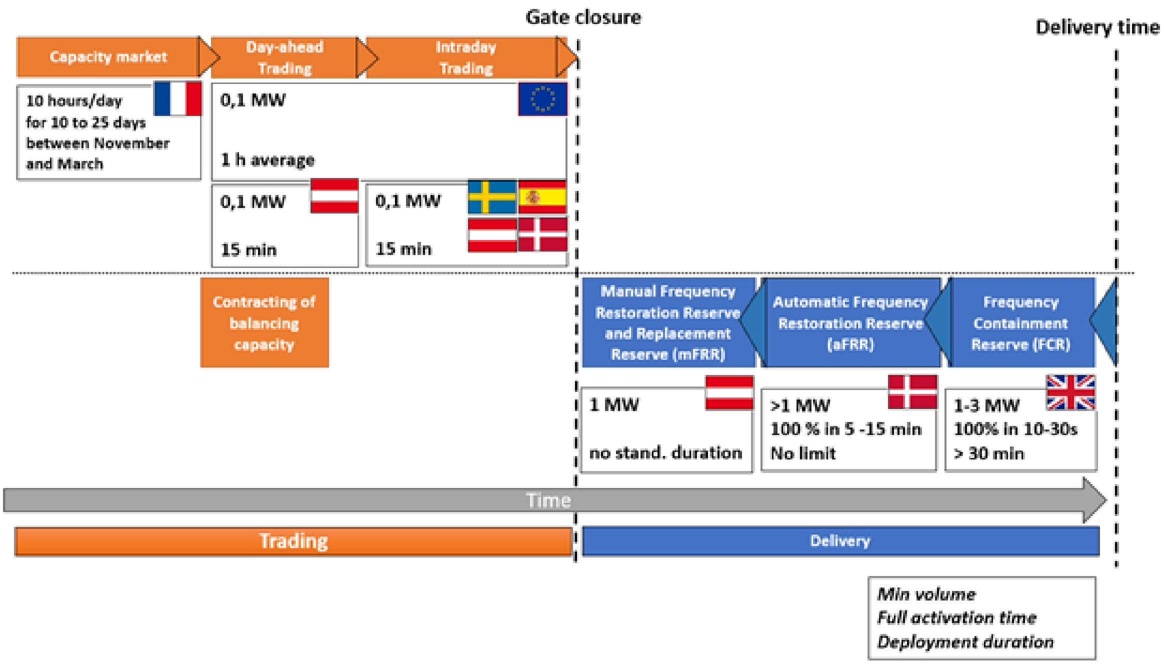

Figure 29: Illustrative overview of some characteristics of the services identified in D3.1

Regarding energy trades (day-ahead and intraday energy markets), the organisation of both types of markets is similar in the considered countries, even if going further in the analysis, some country specificities can be found with respect for instance to the timelines involved and the product duration.

For the other selected services, a larger diversity is observed. Some services such as the capacity requirement mechanisms currently exist only in France, Great Britain, Spain and Sweden (and expected to be implemented soon in Italy) and take very different forms (organised markets, capacity payments and reserves).

Initiatives have been launched by TSOs in order to harmonize the procurement of balancing and frequency regulation services and to support the implementation of the EC guideline on Electricity Balancing, and several ongoing projects address these differences between European countries.

In order to assess whether the technologies and technology couplings, as they are the project's case studies, are suitable to provide services to the electricity grid, the characteristics of such services and of the correspondent market products have been benchmarked in the different case study countries and are summarised in Table 29.

In bold are the current service requirements which appear to be the most constraining for MES and will then be further commented in the following paragraphs.

The characteristics of the products currently traded will be the basis both for the description of the present bottlenecks to service provision and for describing technology improvements, which would be meaningful to maximise this potential. This work will be the subject of the upcoming Deliverable D1.3 "Technological adaptation to flexibility products and guidelines for development".

Table 29: Overview of the characteristics of the services identified in D3.1, and specificities of the products currently provided in the countries analysed in the project. Source of information: D1.3 (Cauret, et al. 2019)

Service	Eligible technologies	Aggregation allowed	Type of product	Min. volume	Max. volume	Deployment duration	Full Activation Time
Day ahead energy markets	All. IT, SE: **Electricity storage not yet allowed**	Yes (upcoming in IT)	Unidirectional	Min. increment: 0.1 MW	DK: 500 MW maximum per block	**1 h** av. Products, block of hours GB: 30 min, 1 hour AT: 15 min possible	Activation according to schedule
Intraday energy markets	All. SE: Electricity storage not yet allowed	Yes (upcoming in IT)	Unidirectional	Min. increment: 0.1 MW	GB: 2000 MW	**15 min.** (AT, DK, ES, SE), 30 min. (DK, SW, GB), 1 h, block of hours	
Capacity requirement mechanisms (only FR, GB, ES and SE. IT upcoming)	FR: producers, aggregators, demand-response with certified capacity. GB: after pre-selection, power plants, electricity storage plants, demand-response	FR: yes below 100 MW. GB: yes, under certain conditions	FR: Unidirectional product, unconditional delivery			FR: capacity availability commitments: 10h/day (7 AM-3 PM; 6 PM – 8 PM) during "PP2" days, which are 10 to 25 weekdays between November and March. Energy delivery through contracts or bids on the energy and balancing markets. GB: stress events longer than 30 min.	
Frequency Containment Reserve	AT, DK, FR: All ES, SE: generators only IT: non intermittent generators > 10 MW GB: transmission-connected generators	Not in IT and ES	Mainly symmetrical. Only positive in DK	AT, FR: 1 MW; DK: 0.3 MW; SE: **0.1 MW**; GB: 1 – **3 MW**	FR: 2.5% Pmax; 150 MW per unit; GB: 50 MW per unit	AT: **> 30 min** FR, ES: > 15 min GB: > 30 min (secondary response)	AT: 100% in 50 s DK: 100% in **30-150 s** FR: 100% in 30 s IT: 100% in 50 s ES: 100% in 15-30 s SE: 100% in 30 s-3 min GB: 100% in 10-30 s
Automatic Frequency Restoration Reserve	IT: **no RES** which cannot be scheduled Often: units with contracts as balancing capacity with TSO Always: technical pre-qualification needed	Not in IT and ES	Mainly symmetrical	DK, FR: **> 1 MW** AT, IT, ES, SE: > 5 MW Min. increment: 1 MW in AT and DK	DK: 50 MW	Generally: no limit IT: > 2 h ES: 15 min until tertiary regulation acts	AT, IT: 5 min DK: **5-15 min** FR: 400-800 s ES: 30 s SE: 2 min
Manual Frequency Restoration Reserve (mFRR)	**Mainly generators**, peak load reserves	RR: Demand response not accepted in ES. (Interruptible)	Bidirectional	AT: 1 MW for first bid, then 5 MW	AT, DK: 50 MW	No standard duration.	

Service	Eligible technologies	Aggregation allowed	Type of product	Min. volume	Max. volume	Deployment duration	Full Activation Time
and Replacement Reserve (RR)	(pumped storage), and aggregated loads IT: no variable RES can be scheduled	Aggregation not accepted in IT		IT, ES, FR*: **10 MW** *FR: derogation for small balancing units: min 1 MW and max 10 MW GB: 1-50 MW			

5.2 Technical suitability to services

In Section 4 technologies installed or to be investigated in the case studies have been characterised and described in terms of their flexibility. In Table 30, basic flexibility parameters such as power ranges, start-up times and ramp rates have been gathered to assess the technologies' capability to cover certain flexibility requirements.

Table 30: Basic technical characteristics of the considered technologies

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 aero-derivative	36-117	5	10-12	82-132%
Heat pump**	0.0005-7.5	3	300	20%
E-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 be expressed as the time within which minimum power volume (in megawatts) has to be provided to the electric grid. As indicated in Figure 30, the gas-to-power and heat-to power concepts are important for frequency control and balancing because of their reactivity and the volume that they are able to provide. In addition, e-boilers, which have the shortest hot-start up time and ramp rate per minute at 100% of nominal power, may play a big role in the market of balancing services. E-boiler and other power-to-heat/cold technologies are relevant for the “short-term” services (DNV GL and CE Delft 2015).

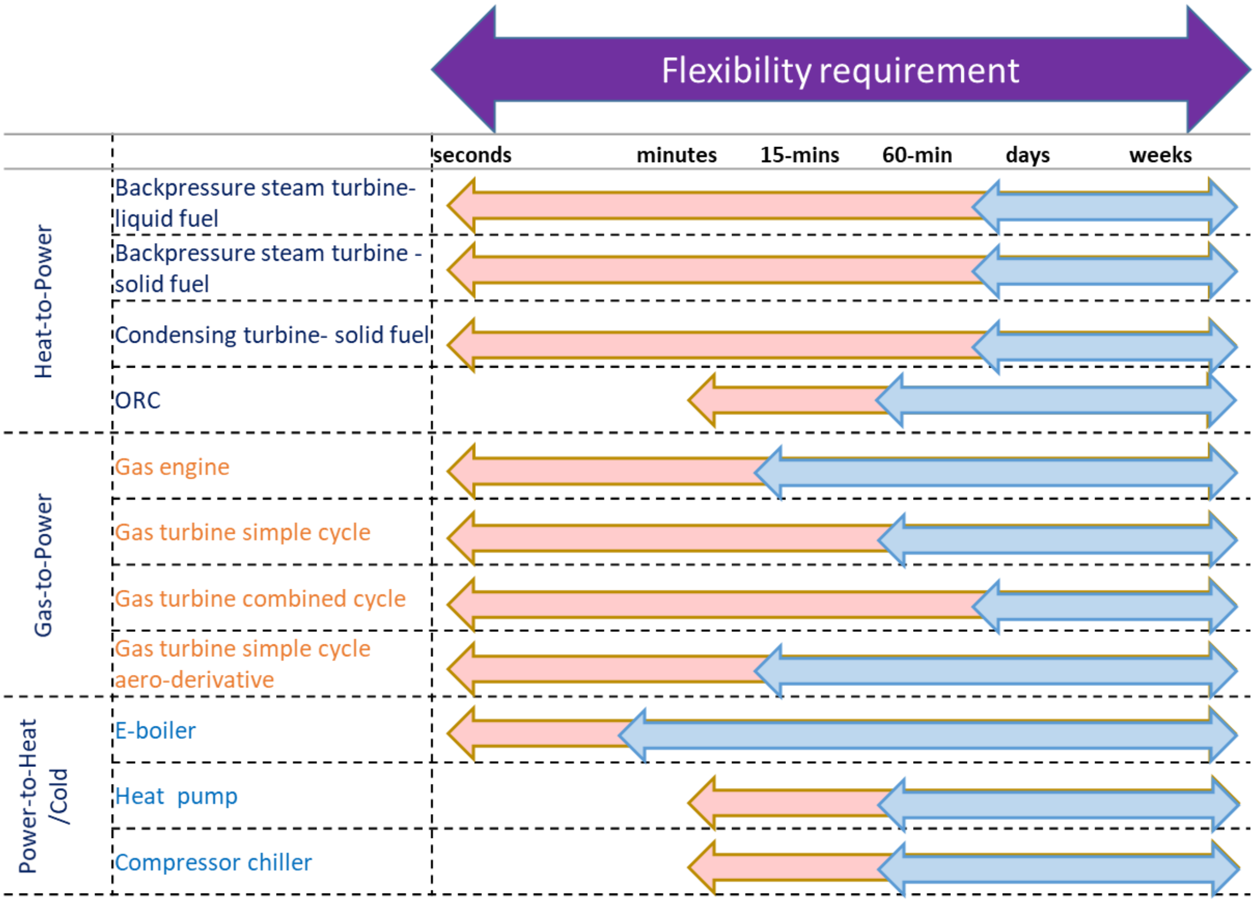

Figure 30: Flexibility options provided by different technologies, orange arrows show capability for running technologies and blue arrows reflect capability including time needed for startup from hot state

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 CCGT 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 31. 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 a big 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 32 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 Frequency Containment Reserve 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.

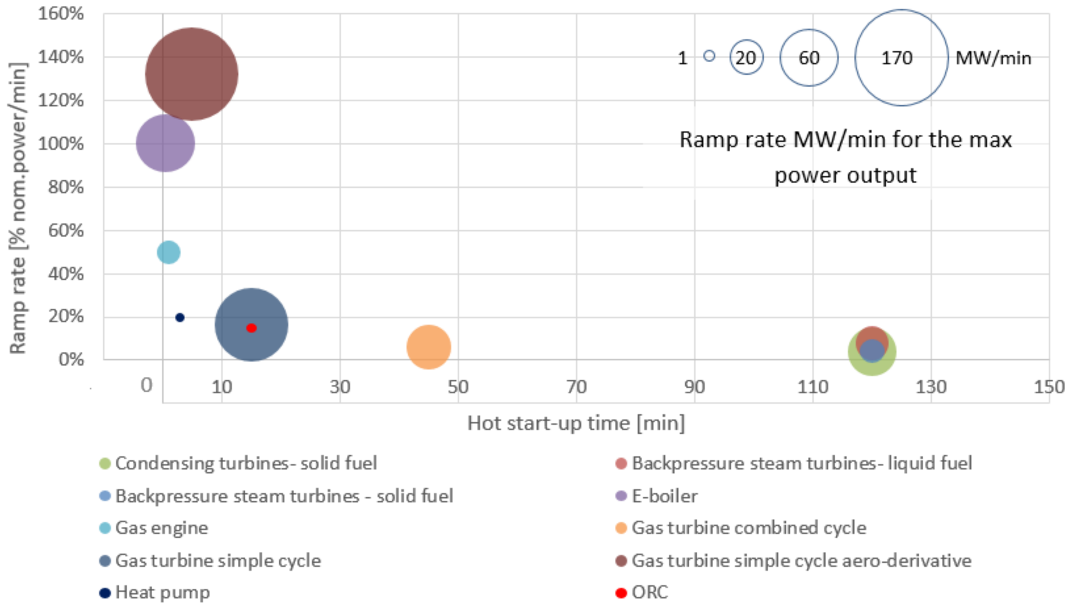

Figure 31: Ramp rates [% nom.power/min] and [MW/min] for the biggest power output as functions of hot start-up time

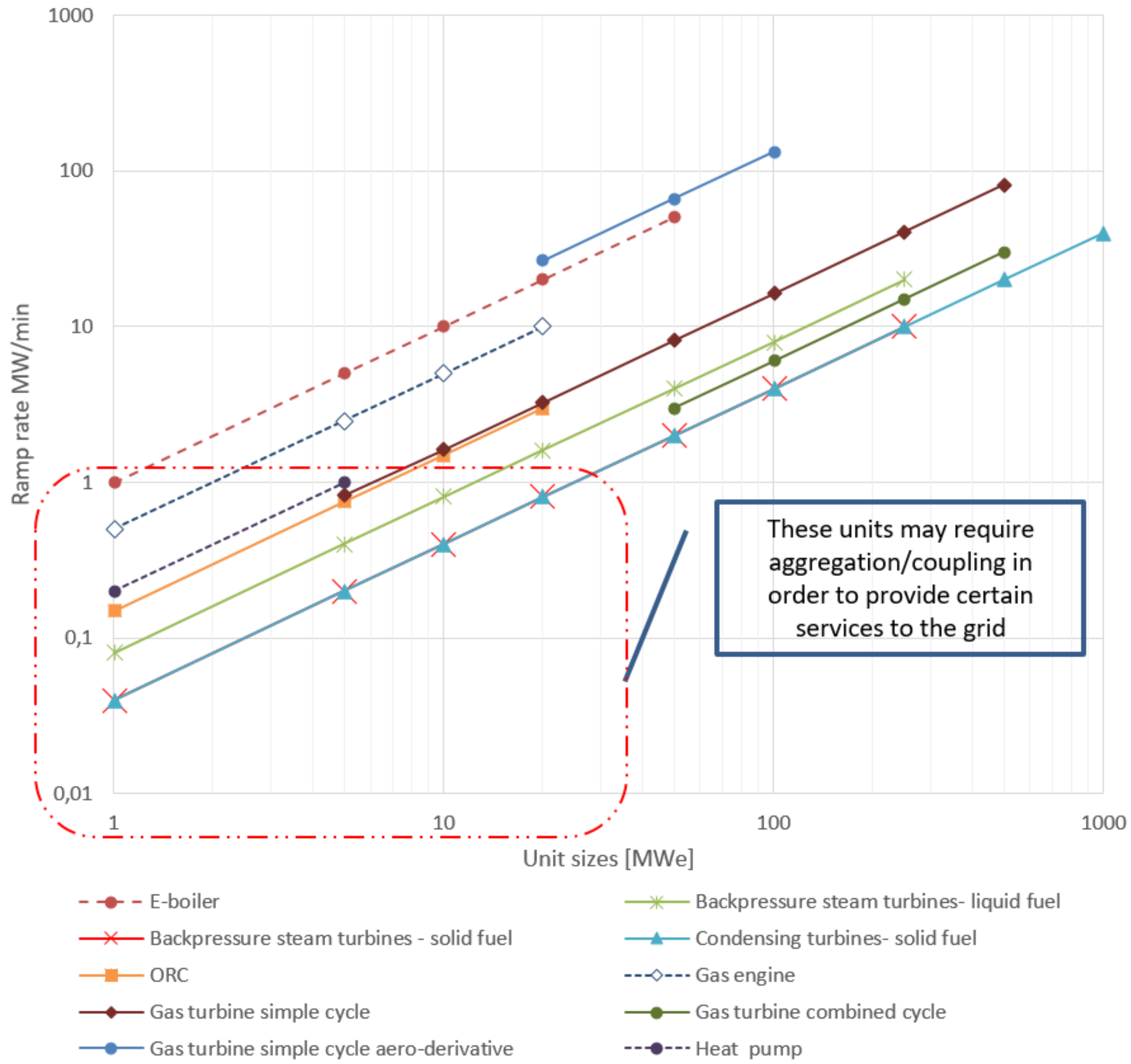

Figure 32: Power range of analyzed technologies and their ramp rates [MW/min]

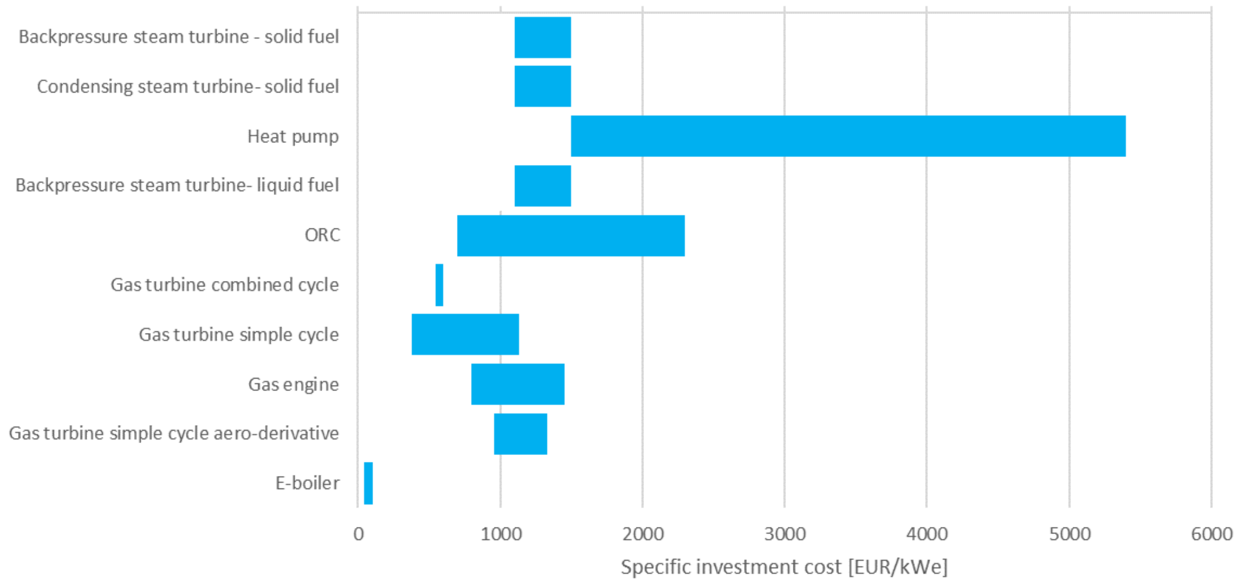

Figure 33: Specific investment cost for studied technologies. Cost for heat pumps was converted from kWth into kWe (of consumed electricity) by dividing the heat production by a COP of 3

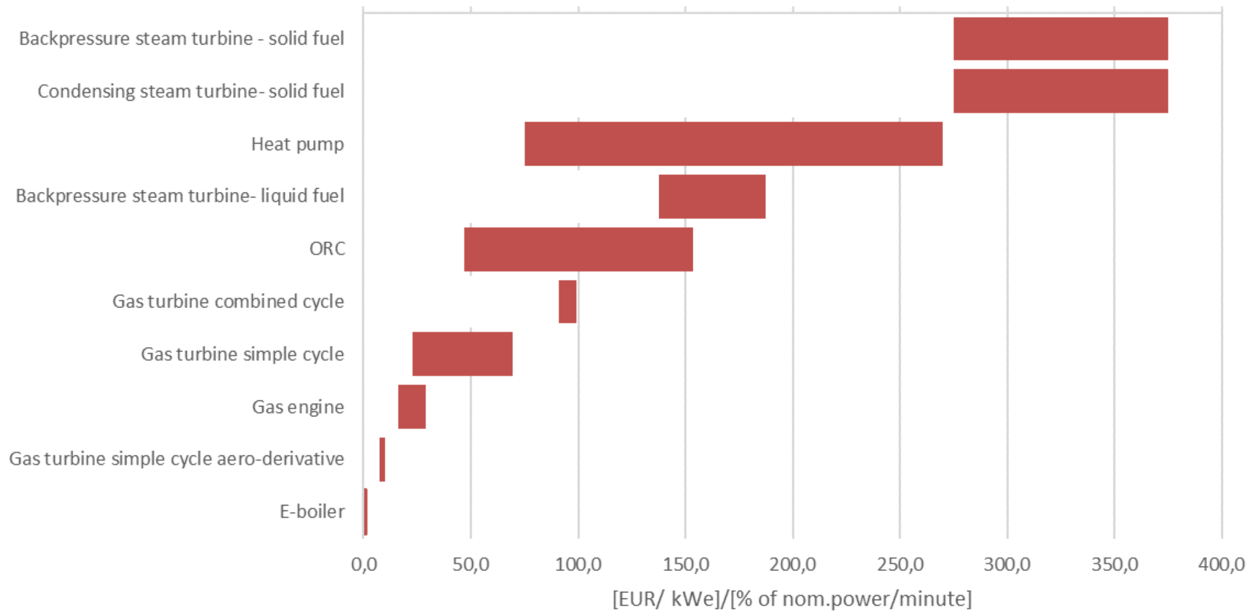

Figure 34: Specific cost of investment divided by ramp rates for different technologies

The specific costs of investment (minimum and maximum values) for studied technologies have then been gathered (Figure 33) and divided by their ramp rate speed [% of nom. power/min]. The result of this operation is shown in Figure 34: the investment cost of reactivity varies between 0.3 for e-boilers up to 375 for solid fuel steam turbines, expressed in [€/kWe]/[% of nom. power/min]. 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, probably the cost of providing ancillary services to the grid may 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. Of course, 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. From a technology coupling perspective, thermal storage is necessary: even though it does not directly provide flexibility to the electricity markets, it enables to deal with a surplus of insufficient heat production, which is important to maintain high overall efficiency.

5.3 Technology bottlenecks and case study improvements

Improvement options leading to a more flexible system are presented in Table 31 for each case study.

These results are based on the data collected during interviews with the case studies' contact points. System configuration characteristics and service characteristics from D1.1 and D3.1 as well as characteristics of the considered technologies that may limit or enhance flexibility provision were also taken into account during the assessment.

Table 31: Overview of the installed capacity of the technologies available in the case studies

Case study	Steam turbines	Gas turbines	Gas turbine- CCGT	Gas engines	Chillers	Heat pumps			Electric boilers	TES	Gas storage
Unit	MWe	MWe	MWe	MWe	MWth	MWth heat	MWth cold	MWe	MWe	MWth	MWth
1 - ME	110**				7	24	20	8.0		2 100	
2 - PM	17.2									0.6-31.5	
	15.3										
3 - HO						0.8		0.25 + 0.003 x n*	0.226 + 0.003 x n*	4	
4 - ACS				15.12		18	13.7	6	10	70	
5 - NPT	109.7	32	520								
6 - EM				1							16.5
7 - PS						15	10	5			

*n is the number of individual units, **peak units of total capacity 280 MWe are excluded

Table 32: Overview of energy produced in the case studies, according to the available data

Case study	Total installed capacity	Heat production	Electricity production	Cold production
Unit	MWe	GWh	GWh	GWh
1 - ME	119.0	1536.0	422.0	25.0
2 - PM	17.2 15.3	548.0	121.9	
3 - HO	0.5	10.1		
4 - ACS	31.1	183.0	n.a.	n.a.
5 - NPT	661.7	n.a.	n.a.	
6 - EM	1.0	8.0	7.7	
7 - PS	5.0	40.0		10.0

Mälarenergi: Biofuel fired cogeneration plants that are heat driven supply heat and electricity to a district heating network. Absorption chillers produce cold that is fed into a district cooling network. In order to avoid bypassing the electricity generator during peak heat demand, a first improvement option is to integrate a thermal storage tank to produce additional electricity. The second option to be studied is the provision of frequency control by distributed heat pumps when heat demand is high. However, the economic viability of this second option is to be first analysed in more depth since electricity – currently a by-product of the heat production - would need to be bought from the grid.

Paper Mill: steam turbines supplied by steam boilers provide steam and electricity to the paper production process. Electricity is purchased from the grid and excess steam is either stored or condensed and recovered in a DH network. An improvement strategy is to install a new steam accumulator that would reduce steam blow-off, reduce fuel consumed for steam generation and increase the flexibility of the steam turbines, thus allowing the provision of frequency control. Another option is to optimize the operation of the whole facility by minimizing gas and electricity peaks.

Hofor: consists of distributed technologies such as electric heat boosters in single houses and HPs (located at substations for domestic hot water production) connected to a district heating network. The improvement option chosen for this case study is the integration of a control and communication interface that allow aggregation and service provision through heat load shifting in multi-storey buildings and single houses by switching on distributed power to heat technologies. FCR cannot be provided due to the deadband constraints for FCR in the Nordic countries including Denmark. Participation in day ahead and intraday energy markets is a very favourable option for Hofor. Mitigation of operational constraints in distribution networks can also be studied considering that are a lot of generation from renewables and small units on site.

ACS: a gas fired CHP, a thermal storage used to smooth the heat peak demand in the morning, and baseload-heat pumps supply heat to a district heating network. Heat pumps are switched on during winter when the demand is high. The products traded are of hourly resolution. There is a day-ahead schedule mainly based on ambient temperature forecast and each product are subdivided into 24 hourly block for the next day. An electric boiler is going to be installed on site in the coming months. Four improvement options have been selected for this case study: 1. Investigation of the different operation modes of the thermal storage, 2. Study of the new pricing models for heat (day/night tariffs) to optimize the heat demand response, 3. Development of predictive model for thermal load forecast that supports accurate forecast and helps mitigate sudden issues happening in the electricity network. ACS cannot participate in the FRC market because its technologies do not meet the requirements in terms of ramp up. 4. Improvement of electrical network which will allow to provide Frequency Containment Reserve.

Neath Port Talbot: it is an industrial park with renewable energy plants (wind and solar), a gas and biomass CCGT and several tertiary and industrial sites. Since it is the only case study for which both gas and electricity networks will be studied, it was decided to investigate how gas-fired generators using fuel from high-pressure gas distribution networks could provide flexibility. The different consumers load will be considered as aggregated gas demand. Since new renewables plants are going to be commissioned, this improvement option is particularly interesting to study.

EMUASA: sludge from the waste water treatment plant are converted into biogas that is further fired in a CHP unit, thus producing heat and electricity that is self-consumed on site by the water treatment process. A gas boiler and electricity drawn from the grid respectively provide heat and electricity peak demand. A small share of the biogas produced is upgraded to biofuels. Power generation from a 520 kW peak PV plant independent from the rest of the plant is fed into the grid. Since EMUASA is located in a rural area and there is not much demand around the site, it is not worth increasing the electricity production and selling it to local consumers. The improvement option chosen for this case study is the integration of a chiller for the production of cold and of a gas storage to exploit flexibility coming from the gas production line. Heat recovery options were excluded because there are no consumers in the area. Upgrade of bio-methane for grid injection was also abandoned because there are legal issues and no local gas grid available in the area.

Paris-Saclay: consists of a geothermal doublet and a centralized peak gas boiler that supply a low temperature district heating network. Thermo-refrigerating pumps are located at each substation and supply heat and cold to the residential buildings connected to the DHN. The improvement options that were selected are as follows: 1. Heat pumps and 2. Thermal storage in buildings and substations. For the Paris Saclay case study, day ahead and intraday are regarded as the most relevant markets.

5.4 Major technological future development drivers

The energy system faces some major changes, driven mainly by political and technological developments. The major mid-term trends identified in the EU Reference Energy scenario are (Capros P 2016):

- Increasing share of RES;
- Higher energy efficiency due to stricter regulation;
- The Energy production mix will move to RES; NG stay the most important fossil fuel;
- Large investments into the energy system (650 billion € between 2020-2030; including grid investments);
- Decarbonisation lead to a CO_2 emission decrease;
- The average retail electricity before taxes is projected to increase to 178 €/MWh in 2030; afterwards, it is nearly constant until 2050;
- Heat and steam demand stays nearly constant.

Political developments comprise legally binding CO_2 reduction goal, the envisaged Emission Trading System, upcoming regulation on energy efficiency for buildings, eco-design as well as CO_2 limits for motorcars.

From the technological point of view, decarbonisation, increasing energy efficiency and RES increase come along with fuel-shift from coal and oil to biomass and NG, electrification of the heat sector, low-temperature DH networks, increasing shares of CHP, as well as a developing cooling market.

Regarding the technologies in the scope of MAGNITUDE, some trends are emerging. A moderate efficiency increase in combination with cost decreases can be assumed for all considered technologies (see Section 4). The market share of P2H technologies and gas-fired systems will increase. For some of the single technologies, some specific additional developments will emerge (have to be considered for the next decade).

The importance of P2H will increase within the next decade, due to RES growth or increasing cost of batteries, to the expected market-entry of P2G technologies not before 2035 and to the general trend of electrification. For heat pumps and chillers, the biggest challenge is the upcoming prohibition of the usage of Fluorinated gases (F-gas) as refrigerants (Official Journal of the European Union 2014). The implementation of environmentally friendly alternatives will affect performance, cost and system integration. Furthermore, high temperature HPs will be available in the market, as well as increased rollout of large HPs for industrial and DH systems. The cooling market will grow significantly, and so the market for chillers.

For electrical boilers, their dynamic behaviour will augment, due to electrical grid requirements; furthermore, small resistance heater ("boosters") sales will increase, due low-temperature DH networks extension. Steam production via electrical boilers will be the biggest technical improvement until 2030.

The conversion of heat to electricity via ORC will be one of the biggest technology changes, with an increase of waste heat use from exhaust gases. Therefore, high temperature material development is required due to higher input temperatures compared to existing geothermal usage today.

Gas technologies will profit from the gas market growth, except gas turbines. The reason is their large capacity, which does not fit to a more decentralized and flexible electricity market due to higher RES penetration; the annual operation hours will be lowered and so the economic viability. Gas engines will profit from this development because of their smaller capacities. A moderate increase of electrical efficiency can also be assumed, as well as lower emissions due to legislative restrictions.

Steam, as mentioned above, will either be provided by power to heat technologies, but also still by gas and biofuels, and less by other fossils. The development of high-temperature materials will lead to a new generation of steam boilers, providing high-energy steam via ultra-super-critical boilers.

Heat storage will gain more and more interest, to overcome daily, weekly and seasonal fluctuations of heat demand in industry and heating networks. While hot water tanks are not likely to change significantly in the future, new steam storage systems are expected to provide significant cost and performance benefits. New concepts like molten salt storage or cement are under investigation to tackle the challenge of high-energy density requirements for steam storage.

Biogas storage and upgrading remain a niche market, although a further cost decrease of upgrading in combination with the high need to reduce CO_2 emissions in the mobility sector can result in some regional concepts for CNG vehicles.

The biggest developments are obviously the system integration of above technologies. The appropriate combination of the above mentioned technologies will increase the overall efficiency of the energy system.

As examples, hot water storage, large HPs and electrical boilers are utilized to a greater extent in DH networks. With improved control strategies and ICT technology, they will contribute to couple heat and power markets. ORC using exhaust heat from combustion processes, solar driven DH networks with seasonal storage and P2H technologies for peak demand provision in the heating period as well as CHP combined with HPs or electrical boilers are other concepts with a bright future. The common point of these concepts is the requirement of flexibility of the power grid, compatibly with the heat demand requirements of the connected heating system.

More difficult to estimate in the future are the regulatory requirements. Besides the national constraints, the level of European harmonization of power and heat markets will go on, but the degree achieved in ten years is still uncertain. Therefore, the upcoming Deliverable D1.3 will address the following issues, on the basis of D1.2 and D3.1:

- Evaluation of if and how innovative market designs can be applied to the above technologies and use cases;
- Investigation on how to improve flexibility products in case they are not compatible with current and future technological constraints;
- Development of recommendations on technologies and systems evolutions to support deployment of flexibility products and improved synergies between sectors.

6 Bibliography

Alstom. 2012. *Successful milestone for Alstoms supercritical coal-fired steam power plant in Karlsruhe.* 15 May. Accessed January 16, 2019. https://www.alstom.com/press-releases-news/2012/5/successful-boiler-pressure-test-at-block-8-of-rheinhafen-dampfkraftwerk-rdk8-karlsruhe-germany.

Antti Uusitalo, Juha Honkatukia, Jari Backman, Sami Nyyssönen. 2015. “Experimental study on charge air heat utilization of large-scale reciprocating engines by means of Organic Rankine Cycle.” *Applied Thermal Engineering, Volume 89*, 5 October: 209-219.

Arturo Castillo Castillo, Imperial College Centre for Energy Policy and Technology. July 2012: REF UKERC/WP/TPA/2013/008. *UKERC Technology and Policy Assessment, Cost Methodologies Project: CCGT Case Study.* Working Paper, UK Energy Research Centre.

B. Kirby, N. Milligan. n.d. “A Method and Case Study for Estimating the Ramping Capability of a Control Area or Balancing Authority and Implication for Moderate or High Wind Penetration.” *WINDPOWER 2005 Conference and Exhibition.* Denver, Colorado: NREL/CP-500-38153.

Bakker, Ernst-Jan, Robert de Boer, Simon Smeding, Niels Sijpheer, and Michel van der Pa. 2013. *Development ofan Innovative 2.5 kW Water-Silica Gel Adsorption Chiller.* Petten: Energy Research Centre of the Netherlands.

BINE Informationsdienst. 2018. *Wärmespeicher ersetzt Dampfkessel .* 27 September. http://www.bine.info/index.php?id=39&no_cache=1&typ=30&artikel=3685&cHash=f802f7c298707c48a2aabab143a81b36.

Bothe, D. 2017. *Der Wert der Gasinfrastruktur für die Energiewende in Deutschland.* FNB Gas e.V.

Brough, Anthony. 2019. “Industrial Gas Turbine Market.” *Western Turbine Users, Inc. 2019.* Dora Partners & Company LLC.

C. Grigg, P. Wong, P. Albrecht, R. Allan, M. Bhavaraju, R. 1999. *The IEEE Reliability Test System-1996. A report prepared by the Reliability Test System Task Force of the Application of Probability Methods Subcommittee.* Power Systems, IEEE Transactions on, 14(3):1010–1020, 1999.

Capros P, De Vita A, Tasios N, Siskos P, Kannavou M, Petropoulos A, Evangelopoulou S, Zampara M, et al. 2016. *EU Reference scenario 2016 - Energy, transport and GHG emissions - Trends to 2050.* Publication report, Luxembourg: European Comission, Directorate-General for Energy, Directorate-General for Climate Action and Directorate-General for Mobility and Transport.

Cauret, L, R Belhomme, P Raux-Defossez, J Eberbach, M Eising, J Steinbesser, JM Pagan Carpe, and S Nösperger. 2019. *D3.1 - Benchmark of markets and regulations for electricity, gas and heat and overview of flexibility services to the electricity grid.* MAGNITUDE project.

Clarke Energy. 2019. *Jenbacher Gas Engines.* Accessed January 15, 2019. https://www.clarke-energy.com/gas-engines/.

Craig S. Brooker, Mitsubishi Hitachi Power Systems Americas. 2017. *Frame versus Aero: Who Wins in Simple Cycle? Mid to Large-size Combustion Turbines.* 07 December. Accessed January 29, 2019. https://www.power-eng.com/articles/print/volume-121/issue-7/features/frame-versus-aero-who-wins-in-simple-cycle-mid-to-large-size-combustion-turbines.html?fbclid=IwAR3rLc1RwEKOkoR1xqaFKxBbvyZ-U6P4RIETlbq02Az0vSdOUMR_ciN3_MQ.

D. Proctor, POWER. 2018. *Efficiency Improvements Mark Advances in Gas Turbines.* 01 March. Accessed January 08, 2019. https://www.powermag.com/efficiency-improvements-mark-advances-in-gas-turbines/?printmode=1.

Danish Energy Agency. 2016. *Technology Data Catalogue for Electricity and district heating production.* Catalogue, Copenhagen, Denmark: Danish Energy Agency.

Danish Energy Agency. 2018. *Technology Data for Energy Storage.* Catalogue, Copenhague: Danish Energy Agency.

David, A. 2017. "Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems." *Energies* 578.

Department for Business, Energy & Industrial Strategy. 2018. *Digest of UK Energy Statistics (DUKES) 2018 Chapter 5: Electricity.* July. Accessed January 14, 2019. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/736148/DUKES_2018.pdf.

—. 2018. *Updated energy and emissions projections: 2017.* 02 January. Accessed January 7, 2019. https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2017.

DNV GL and CE Delft. 2015. *System Integration –Hybrid Energy Infrastructures.* Final report GCS.103750, Groningen: Dutch Ministry of Economic Affairs, Netherlands Enterprise Agency (RVO).

Dr. Artur Ulbrich, Any Jones, Christian Schäferkordt, Stuart Simpson at UNIPER. 2016. "Increasing competitiveness of CCGT plants in a dynamic market: An owner's approach." *8th International Gas Turbine Conference.* Brussels : Uniper.

Drew, R. 2018. *International Turbomachinery- tough times for gas turbines.* 05 July. Accessed January 19, 2019. https://www.turbomachinerymag.com/tough-times-for-gas-turbines/.

ECOFYS. 2013. *Heat pump implementation scenarios until 2030.* Cologne: ECOFYS Germany GmbH.

Eggart, Justin, Christopher E. Thompson, Jerry Sasser, and Mardy Merine. 2017. *Heavy-Duty Gas Turbine Operating and Maintenance Considerations.* GER-3620N (10/17), Atlanta, GA: GE.

2010. "Energy Technology Systems Analysis Programme." *Technology Brief 04- Combined Heat and Power.* May. https://iea-etsap.org/E-TechDS/PDF/E04-CHP-GS-gct_ADfinal.pdf.

EnergyNest. n.d. *Thermal Battery System.* Accessed January 18, 2019. http://www.energy-nest.com/.

Enogia. 2019. *Products.* Accessed January 15, 2019. http://www.enogia.com/.

European Technology Platform on Renewable Heating and Cooling. 2012. *Strategic research priorities for cross-cutting technology.* Brussels: European Technology and Innovation Platform.

Evans, Simon. 2018. *Analysis: UK government slashes outlook for new gas power plants.* 08 Januar. Accessed December 17, 2019. https://www.carbonbrief.org/analysis-uk-government-slashes-outlook-for-new-gas-power-plants.

Feldmueller, Dr. Andreas. 2017. "Flexibility of coal and gas fired power plants." 18 September. Accessed January 17, 2019. https://www.cleanenergyministerial.org/sites/default/files/2018-01/Andreas%20Feldmueller%20Siemens.pdf.

Florida Power & Light Company. 2019. "An FPL Technical Primer." *Air-Cooled Chillers.* Accessed 2019. https://www.fpl.com/business/pdf/air-cooled-chillers-primer.pdf.

—. 2019. "An FPL Technical Primer." *Water-Cooled Chillers.* Accessed 2019. https://www.fpl.com/business/pdf/water-cooled-chillers-primer.pdf.

GE Power. 2019. *AERODERIVATIVE & HEAVY DUTY Gas Turbines.* Accessed January 28, 2019. https://www.ge.com/power/gas/gas-turbines.

—. 2016. *Breaking the Power Plant Efficiency Record- GE & EDF unveil a game-changer at Bouchain.* https://www.ge.com/power/about/insights/articles/2016/04/power-plant-efficiency-record.

—. 2019. *GE Power Steam Turbines.* Accessed January 15, 2019. https://www.ge.com/power/steam/steam-turbines.

—. 2018. *Power Outlook: Natural Gas Key To Future Power Grid.* 05 December. Accessed January 16, 2019. https://www.ge.com/reports/power-outlook-natural-gas-key-future-power-grid/.

Goldman Energy. 2016. *How does an absorption chiller work?* Accessed December 12, 2018. http://goldman.com.au/energy/company-news/how-does-an-absorption-chiller-work.

Green, Adam. 2017. *CHP Cheat Sheet - Gas Engines & Gas Turbines.* 27 July. Accessed Januar 16, 2019. https://adgefficiency.com/cheat-sheet-gas-engine-gas-turbine-chp-energy-basics/.

Große, Robert, Christopher Binder, Stefan Wöll, Roman Geyer, and Steffen Robbi. 2017. *Long term (2050) projections of techno-economic performance of large-scale heating and cooling in the EU.* ISBN 978-92-79-75771-6, doi:10.2760/24422, JRC109006, Luxembourg: Publications Office of the European Union.

Grzebielec, Andrzej, Artur Rusowicz, Maciej Jaworski, and Rafał Laskowski. 2015. “Possibility of using adsorption refrigeration unit in district heating network.” *Archives of Thermodynamics, Vol. 36* 15-24.

Henderson, Colin. 2014. *Increasing the flexibility of coal-fired power plants.* London: IEA Clean Coal Centre, CCC/242.

International Energy Agency. 2010. “The Energy Technology Systems Analysis Program, International Energy Agency.” *IEA ETSAP - Technology systems analysis programme Combined Heat and Power.* Accessed January 22, 2019. https://iea-etsap.org/E-TechDS/PDF/E04-CHP-GS-gct_ADfinal.pdf.

IRENA. 2013. *Heat Pumps - Technology Brief.* IRENA.

Johnson Control. 2019. *Industrial & Commercial HVAC Chillers for Sustainable Solutions.* Accessed January 09, 2019. https://www.johnsoncontrols.com/hvac-equipment/chillers.

Johnson Controls. 2015. “Chiller Plant Applications.” 17 November. Accessed January 09, 2019. https://www.airah.org.au/Content_Files/Divisionmeetingpresentations/QLD/Qld-17-11-15-Stuart-Kirkwood.pdf.

—. 2018. “YORK® Commercial & Industrial HVAC 2018.” *Johnson Controls.* Accessed February 1, 2019. https://www.johnsoncontrols.com/-/media/jci/global-capabilities/be/files/be_york_industrial_commercial_hvac_2018.pdf.

Kloepper-Therm. 2018. *Hot water boiler – type series HWE.* December. https://www.kloepper-therm.de/fileadmin/pdf/HWE-Flyer__HWE0001-00-EN_10-13_.pdf.

Köhler, Benjamin & Dengler, Jörg & Dinkel, Arnulf & Azam, Mauman & Kalz, Doreen & Bonato, Paolo & Tobias, Fleitern & Steinbach, Jan & Ragwitz, Mario & Arens, Marlene & Aydemir, Ali & Elsland, Rainer & Frassine, Clemens & Herbst, Andrea & Hirzel, Simon & K. 2017. *Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables) - Work package 2: Assessment of the technologies .* Prepared for: European Commission under contract N ° ENER/C2/2014-641, European Commission (ENER).

Laser Focus World Magazine. 2004. *Proper capacity control improves chiller performance.* 06 January. Accessed February 12, 2019. https://www.laserfocusworld.com/articles/print/volume-40/issue-6/features/chillers/proper-capacity-control-improves-chiller-performance.html.

Lecompte, Steven, Oyeniyi A. Oyewunmi, Christos N. Markides, Marija Lazova, Alihan Kaya, Martijn van den Broek, and Michel De Paepe. 2017. "Case Study of an Organic Rankine Cycle (ORC) for Waste Heat Recovery from an Electric Arc Furnace (EAF)." *Energies, Volume 10, Issue 5*, 07 May: 649.

Li, Hailong, Worrada Nookuea, Pietro Elia Campana, Jinyue Yan, Nicole Pini, Paul Haering, Stephan Seidelt, Karol Witkowski, and et al. 2019. *D1.1 - Cartography of the flexibility services provided by heating/cooling, storage and gas technology and systems to the electricity system.* Magnitude project.

M. Steen; Joint Research Centre. 2017. *Greenhouse gas emissions from fossil fuel fired power generation systems.* Study, European Commission, EUR 19754 EN.

Maier, M. 2018. *Metaanalyse Die Rolle erneuerbarer Gase in der Energiewende.*

Mate, Benjamin. 2015. *GEA Reports, Geothermal Energy Association Issue Brief: Firm and Flexible Power Services Available from Geothermal Facilities.* May. http://geo-energy.org/reports/2015/Firm%20and%20Flexible%20Power%20Services%20from%20Geothermal.pdf.

Miguel Angel, Gonzalez-Salazar, Trevor Kirsten, Lubos Prchlik. 2018. "Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables." *Renewable and Sustainable Energy Reviews, Volume 82, Part 1,*, February: 1497-1513.

Mike Welch, Siemens Industrial Turbomachinery Ltd. 2016. "Flexible Power Generation for Grid Support utilizing the Aero-derivative Gas Turbines." *Power Generation Week 2016.* Siemens. Flexible Power Generation for Grid .

Modern Power Systems. 2016. *Preparing for the next phase at Stadtwerke Kiel's super- flexible multi-purpose plant.* 10 November. Accessed February 05, 2019. https://www.modernpowersystems.com/features/featurepreparing-for-the-next-phase-at-stadtwerke-kiels-super--flexible-multi-purpose-plant-5665710/.

—. 2018. *Why stationary power is a growth market for gas engines.* 11 May. Accessed February 06, 2019. https://www.modernpowersystems.com/features/featurewhy-stationary-power-is-a-growth-market-for-gas-engines-6140544/.

N. Saito, N. Komai, Y. Sumiyoshi, Y. Takei, M. Kitamura and T. Tokairin. 2015. "Development of Materials for Use in A-USC Boilers." *Mitsubishi Heavy Industries Technical Reviev Vol. 52 No. 4*, December: 27-36.

Official Journal of the European Union. 2014. "EUR-Lex Access to European Union law." *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 Text with EEA relevance.* 16 April. http://data.europa.eu/eli/reg/2014/517/oj.

PARAT. 2018. *https://www.parat.no/en.* 15 December. https://www.parat.no/en.

Power Engineering International. 2015. *The rise and rise of gas engines.* 22 May. Accessed February 04, 2019. https://www.powerengineeringint.com/articles/print/volume-23/issue-5/features/the-rise-and-rise-of-gas-engines.html.

Power Technology. 2003. *Baglan Bay CCGT Power Plant.* Accessed December 17, 2018. https://www.power-technology.com/projects/baglan/.

Prognos. 2011. *Beitrag von Wärmespeichern zur Integration erneuerbarer Energien.* Berlin: AGFW.

Ralf Grosshauser, Thermamax GmbH. 2016. *Turbines vs. Reciprocating Engines.* 17 November. Accessed January 16, 2019. https://www.power-eng.com/articles/print/volume-120/issue-11/features/turbines-vs-reciprocating-engines.html.

SEDC. 2017. *Explicit Demand Response in Europe: Mapping the Markets 2017.* Brussels: Smart Energy Demand Coalition.

Seitz, A. 2017. "Thermische Energiespeicher für bedarfsgerechte Energiebereitstellung in Gebäuden und in der Industrie." *FVEE-Jahrestagung.* Berlin: FVEE.

Shunchao Wang, Laust Riemann. 2018. *Thermal Power Plant Flexibility, a publication under the Clean Energy Ministerial Campaign.* Paris: The Clean Energy Ministerial Advanced Power Plant Flexibility.

Siemens AG. 2019. *Heat ReCycle Solutions - The cleaner and efficient alternative.* https://new.siemens.com/global/en/products/energy/power-generation/power-plants/heat-recycle-solutions.html.

—. 2014. *Waste Heat Recovery with Organic Rankine Cycle Technology.* Accessed December 12, 2018. https://www.energy.siemens.com/mx/pool/hq/power-generation/steam-turbines/downloads/brochure-orc-organic-rankine-cycle-technology_EN.pdf.

2018. *Siemens steam turbine portfolio.* Accessed January 15, 2019. https://www.siemens.com/content/dam/webassetpool/mam/tag-siemens-com/smdb/power-and-gas/steamturbines/steam-turbine-product-overview-01-2018.pdf.

Spirax Sarco. 2016. "Grundlagen Dampfspeicher." July. Accessed January 10, 2019. http://www.spiraxsarco.com/global/de/Resources/Documents/Grundlagen%20Dampfspeicher.pdf.

Sterner, M., Stadler, I. 2017. *Energiespeicher Bedarf, Technologien, Integration.* Heidelberg: Springer Vieweg.

SUMMERHEAT. 2009. *Meeting cooling demands in SUMMER by applying HEAT from cogeneration.* The publishable report is a product of the SUMMERHEAT project EU Intelligent Energy Europe Programme EIE-06-194, Berliner Energieagentur GmbH.

Sylvain Quoilin, Martijn Van Den Broek, Sébastien Declaye, Pierre Dewallef, Vincent Lemort. 2013. "Techno-economic survey of Organic Rankine Cycle (ORC) systems." *Renewable and Sustainable Energy Reviews, Volume 22*, June: 168-186.

Syrri, Angeliki, Henrik Bindner, Hailong Li, Jakub Jurasz, Jinyue Yan, and Ying Yang. 2019. *D6.1 - KPIs and assessment procedure.* Magnitude project.

Tartière, Thomas, and Marco Astolfi. 2017. "A World Overview of the Organic Rankine Cycle Market." *Energy Procedia, Volume 129* (Energy Procedia) 2-9.

Thorsen, Jan Eric, and Torben Schmidt Ommen. 2018. *Field experience with ULTDH substation for multifamily building.* Energy Procedia.

Triogen. 2019. *Products.* Accessed January 21, 2019. http://www.triogen.nl/technology/triogen-our-products.

Turboden. 2018. *Waste Heat Recovery.* Accessed December 18, 2018. https://www.turboden.com/applications/1053/waste-heat-recovery.

Tvärne, Andreas, Henrik Frohm, and Anders rom Capital Cooling Energy Service AB,Sweden Rubenhag. 2015. *EU DISTRICT COOLING MARKET AND TRENDS.* Project report, RESCUE–RENEWABLE SMART COOLING FOR URBAN EUROPE.

U.S. Department of Energy. 2017. *Combined Heat and Power Technology Fact Sheet Series- Absorption Chillers for CHP Systems.* Accessed December 03, 2018. https://www.energy.gov/sites/prod/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf.

—. 2016. *Combined Heat and Power Technology Fact Sheet Series- Gas Turbines.* Accessed January 15, 2019. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Gas%20Turbine.pdf.

—. 2016. *Combined Heat and Power Technology Fact Sheet Series- Reciprocating Engines.* Accessed January 15, 2019. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Recip%20Engines.pdf.

—. 2016. *Combined Heat and Power Technology Fact Sheet Series- Steam Turbines.* Accessed January 15, 2019. https://www.energy.gov/sites/prod/files/2016/09/f33/CHP-Steam%20Turbine.pdf.

VDE. 2015. *Potenzial für Strom im Wärmemarkt bis 2050.* Frankfurt: VDE.

Wärtsilä. n.d. *Combustion Engine vs. Gas Turbine: Part Load Efficiency and Flexibility.* Accessed January 16, 2019. https://www.wartsila.com/energy/learning-center/technical-comparisons/combustion-engine-vs-gas-turbine-part-load-efficiency-and-flexibility.

—. n.d. *Combustion Engine vs. Gas Turbine: Startup time.* Accessed January 15, 2019. Combustion Engine vs Gas Turbine: Startup Time.

Welch, Michael, and Andrew Pym. 2015. *Improving the Flexibility and Efficiency of Gas Turbine-Based Distributed Power Plants.* 14 09. Accessed 01 10, 2019. https://www.power-eng.com/articles/print/volume-119/issue-9/features/improving-the-flexibility-and-efficiency-of-gas-turbine-based-distributed-power-plants.html.

Wikipedia. 2019. january. https://en.wikipedia.org/wiki/Heat_pump.

Appendix A1 – Factsheets. Complete template

General technology factsheet template

Parameter	Unit
Power output Thermal (th.) or electrical (el.) power production	kW th. / el.
Operating temperature input Inlet temperature of the working fluid	°C
Operating temperature output Outlet temperature of the working fluid	°C
Minimum load Minimum thermal or electrical power which can be steadily produced by the technology (corresponding to the power produced at the bottom of the controllable range)	%
Controllable range Difference between full/nominal load and minimum load.	%
Net Energy Efficiency for max load level Ratio between the useful energy (such as electricity, fuel and heat, which can be sold to customers) output and the total energy input for max load level	%
Net Energy Efficiency for min load level The ratio of the useful energy (such as electricity, fuel and heat, which can be sold to customers) output to the total energy input for min load level	%
Cold start up time- electricity The period of time after which the unit starts either producing or consuming electricity. Recovery time after shutdown, cold state.	min
Hot start up time- electricity The period of time after which the unit starts either producing or consuming electricity. Recovery time after shutdown, hot state.	min
Cold start up time- heat The period of time a unit takes to be heated up to the normal operating temperature. Recovery time after shutdown, cold state.	min
Hot start Up time- heat The period of time a unit takes to be heated up to the normal operating temperature. Recovery time after shutdown, hot state.	min
Ramp rate up (charging rate) The rate of change in instantaneous output from a unit	% nom power/ s
Ramp rate down (discharging rate) The rate of change in instantaneous output from a unit	% nom power/ s
Power fluctuation The deviation of power output beyond a certain range from the set value.	kW th. / el. +/-

Parameter	Unit
Voltage Excursions The deviation of voltage in a certain range.	V +/-
Expected lifetime Number of equivalent full-load hours during which a piece of equipment is expected to run before being replaced	h
Specific cost of investment Ratio between the investment cost of a piece of equipment and its nominal useful power (electrical or thermal power, depending on whether the equipment is installed to produce electricity or heat/cold)	€/kW output (el/th)
Operational costs - fixed Operational costs which do not change with an increase or decrease of energy produced/consumed by the piece of equipment. Typically: insurances, leasing, depreciation of assets, permanent workers.	€/kW output (el/th)
Operational costs - variable Operational costs which depend on the energy produced/consumed by the piece of equipment. Typically: fuel costs, abatement systems' cleaning, emission-related taxes.	€/kWh output (el/th)
CO2 footprint/kWh el. Equivalent CO_2 emissions associated to the electricity production	gCO2/kW el.
CO_2 footprint/kWh th. Equivalent CO_2 emissions associated to the heat/cold production	gCO2/kW th.

Case Study factsheet template

Parameters	Unit	Case study			Identified bottlenecks	Other comments
		Min.	Aver.	Max.		
Number of activations per day	number/day					
Max. duration of an activation	min					
Recovery time between activations	min					
Active power fluctuation in % of controllable flexibility (or control error)	%					
Rebound effect (power) in % of activation power	%					
Rebound effect (duration) in % of activation duration	%					
Operational hours	h/year					

The number of hours that the system is running to produce electricity and heat over a year.							
Running Plant Factor The running plant factor of a generation unit is the ratio of the actual energy output of a generation unit over a period of time to its potential output if it had operated at full nameplate capacity during the period in which it has been operated.	%						
Operating cycle The duration of the operating cycle, i.e. the time between two refueling/overhaul outages	h						
Load Factor Load Factor is an indicator of how steady an electrical load is over time	+/- nom power %/ hour ?						
Share of electrical energy produced by renewable sources The calculation of the share of energy from renewable sources using data on the level of the energy available for final consumption represents the ratio of renewable energy put at the disposal of end-users to the total amount of energy available to end-users (for energy and non-energy purposes). This is measured at the level of energy actually at the disposal of end-users (after transformation from primary energy form to the end-use form) and all electricity is counted as not renewable.	%						