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# Analysis of the potential for Power-to-Heat/Cool applications to increase flexibility in the European electricity system until 2030

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# ABBREVIATIONS

| | |
|---|---|
| CAES | Compressed Air Energy Storage |
| CCGT | Cominded Cycle Gas Turbine |
| CHP | Combined Generation of Heat and Power in Co-generation Plants |
| $CO_2$ | Carbon Dioxide |
| COP | Coefficient Of Performance |
| CPI | Current Policy Implemention |
| DHC | District Heating and Cooling |
| DM | Demand Management |
| DSM | Demand Side Management |
| DSO | Distribution System Operator |
| DSR | Demand Side Response |
| EE | Energy Efficiency |
| EEG-Umlage | Erneuerbare Energien Gesetz-Umlage |
| EER | Energy Efficiency Ratio |
| EHPA | European Heat Pump Association |
| EnBW | Energie Baden-Württemberg |
| EPBD | Energy Perfomance of Buildings |
| ETS | Emission Trading Scheme |
| EU | European Union |
| EUR | Euro € |
| EWI | Energiewirtschaftliches Institut |
| FIT | Feed-In-Tariff |
| GHG | Greenhousegas |
| GW | Gigawatt |
| GWh | Gigawatt hour |
| H/C | Heat/Cool |
| HP | Heat pump |
| HVAC | High Voltage AlternatingCurrent |
| HVDC | High Voltage Direct Current |
| IAE | International Energy Agency |
| IT | Information Technology |
| kV | Kilovolt |
| kW | Kilowatt |
| MS | Member State |

| | |
|---|---|
| MW | Megawatt |
| NREAP | National Renewable Energy Action Plan |
| NZEB | Nearly Zero Energy Building |
| O&M | Operations and Maintenance |
| OPEX | Operational Expense |
| ORC | Organic Ranking cycle |
| PCM | Phase Change Material |
| PEF | Primary Energy Factor |
| Pj | Peta Joule |
| Pmin | Minimum Power |
| PP | Power Plant |
| PS | Pumped Hydro Storage |
| PtC | Power-to-Cool |
| PtG | Power-to-Gas |
| PtH | Power-to-Heat |
| PtH/C | Power-to-Heat/Cool |
| PV | Photovoltaic |
| R&D | Research and Development |
| RE | Renewable Energy |
| RES | Renewable Energy Source |
| RES-E | Renewable Energy Source-Electricty |
| SET | Strategic Energy Technologies |
| SMES | Superconducting Magnetic Energy Storage |
| T&D | Transmission and Distribution |
| TES | Thermal Energy Storage |
| TSO | Transmission System Operator |
| TWh | Tera Watt Hour |
| TWL | Technische Werke Ludwigshafen |

# EXECUTIVE SUMMARY

The objective of this report is to assess the potential contribution of Power-to-Heat/Cool applications (PtH/C) to the flexibility in the European electricity system until 2030. The heating and cooling sector accounts for the majority of final energy consumption in the European Union and therefore will play a central role in achieving policy goals concerning climate change mitigations. Electrification of the heating and cooling sector may be an appropriate pathway for decarbonisation of this sector, while at the same time proving additional flexibility to the electricity system.

This report first gives a general overview over the energy sector and in particular over the heating and cooling sector in Europe. Different PtH/C applications with their techno-economic characteristic are described and compared with other flexibility options. The following potential analysis is based on two approaches. The first approach for determining the PtH/C potential is based on a literature review for Europe and some selected EU member states. The second approach is an own quantitative estimation for the selected member states. Afterwards, the regulatory framework in place, that can support or hinder PtH/C, is described. The report ends with conclusions and policy recommendations.

The analysis is based on historical and forecasted data for final energy consumption in the heating and cooling sector shows that the highest theoretical potential for PtH lies in replacing conventional energy carriers for space and process heating. The theoretical potential for PtC is much smaller compared to PtH, due to the smaller share of cooling in final energy consumption.

There are different technologies for converting electricity to heat or cool. In general, the PtH/C applications can be differentiated into large and small scale applications.  By adding a thermal energy storage (TES) to the PtH/C system, additional flexibility can be provided to the system.

Comparing PtH/C to other flexibility options like demand side management, electricity storages, power to Gas (PtG) and flexibility options on the supply side, it can be stated that PtH/C technologies have a high level of maturity. The technology can be easily implemented and is generally cost competitive compared to other flexibility options.

The literature review on the European potential for PtH/C reveals a wide range of the potentials. In general, it seems that the potential for electricity load reduction is far smaller than for a load increase. The potential for PtH/C varies significantly across European member states. Therefore, the literature review is extended for some selected European countries.

The quantitative approach is based on hourly load profiles for electricity and heat. On the one hand, the PtH potential through thermal energy storages in district heating networks is assed. On the other hand, the potential that might arise due to the use of excess electricity, that otherwise would have been curtailed, is calculated. The total calculated potentials in district heating for Denmark, Germany, Austria, the Netherlands, France and Italy are varying due to the inhomogeneous nature of the European energy system and different weather conditions.

In the European Union, there is no direct or specific legislative regulation addressing the heating and cooling sector, however, it is addressed in several Directives. Thermal energy storages used for heating and cooling (H/C) should be recognised as sources of both, flexibility and efficiency in the system. Electric boilers and heat pumps could also be recognised as new modes of flexibility in the system at times of excess electricity generation. Exemptions from fees and taxes or adapted grid usage fees can be considered as a way to promote the market penetration of PtH/C.

# I. INTRODUCTION

Heating and cooling (H/C) accounts for more than half of final energy consumption in the EU and therefore plays a central role in achieving energy policy goals like climate change mitigation, security of supply and competitiveness. In total, final energy demand in the EU28 amounted to about 12,821 TWh in 2012, of which around 6,500 TWh were used for H/C purposes [1]. A potential pathway to decarbonise the H/C sector is using electricity production from renewable sources. In addition, coupling the power and the heat system is also beneficial for the electricity system's flexibility, because surplus electricity, that hardly could be consumed otherwise, can be used in the heat sector.

The European power system is currently experiencing new challenges due to growing shares of intermittent renewable energy sources, mainly from wind and photovoltaics. Not only the intermittent nature of renewable sources, but also current regulations affect the technical stability of the system. The intermittent renewable energy sources (RES) in general have priority dispatch, meaning that they can feed in electricity to the grid whenever they produce. Thus, the renewable feed-in is not necessarily correlated with the electricity demand. For these and other reasons, renewable electricity production will challenge the stability of the power system.

The stability of the system can only be guaranteed if adequate amounts of flexibility can be provided. Among other flexibility solutions, PtH/C (power-to-heat/cool) is a favourable option. PtH/C technologies, such as electric boilers, heat pumps and storage tanks, which are scalable from large to small might be promising option. Particularly electric boilers have comparatively low investment expenditures and consequently are able to operate profitably with only a few full load hours, which is important for making use of excess electricity. On the other hand, heat pumps have the advantages of converting power more efficiently and allowing both heating and cooling. In addition to these, due to their short response times PtH/C technologies are suitable for the provision of ancillary services. However, the deployment levels are lower than for competing heating technologies such as gas, due to economic reasons.

The required flexibility in the electricity system combined with the heat demand serves as the basis for analysing the potential of flexible PtH/C in Europe in this report. PtH/C technologies provide simultaneous benefits to both the heating and the electricity sector and may facilitate the integration of renewable sources into the energy system. However, PtH/C applications can be considered as a resource that has not yet been effectively pursued within energy policy. Furthermore, non-technological barriers exist as well such as historically evolved consumer behaviours or political decisions.

After a description of the current and possible future situation of the European energy system, this report investigates the PtH/C technologies and their role within the Energy system in detail. A comparative analysis of different PtH/C technologies as well as an assessment of these technologies compared to other flexibility options delivers insights regarding the PtH/C potential in Europe. These analyses mainly focus on techno-economic differences and do not cover social aspects such as acceptance of the individual technologies. The mechanisms and regulations necessary to incentivize PtH/C and related business models are also analysed. However, the main focus of this policy report is set on the potential analyses of the PtH/C technologies, which provide flexibility to the electricity system.

Chapter II provides an overview of the energy sector with a particular focus on the heating and cooling sector in Europe and the potential development of the energy, heat and electricity sectors in all member states. This chapter describes and discusses the regulatory framework in place and the existing barriers against the exploitation of PtH/C potential. In addition, the increased need for flexibility in electricity systems is explored and existing solutions are presented. Heat demand and required flexibility in the electricity system serve as a basis for analysing the potential for flexible PtH/C in Europe.

Chapter III includes a detailed presentation of different PtH/C technologies including techno-economic parameters as well as possible developments until 2030. A comparison of PtH/C technologies and an assessment of PtH/C technologies in relation to other flexibility options are carried out.

Chapter IV presents existing business cases and pilot projects on PtH in different European countries and summarizes the policy recommendations that can incentivize these business cases.

Chapter V allows insights to be drawn on the evolution of PtH/C technologies from now to 2030 in the light of the current status and expected evolutions in entire Europe and some selected member states. It analyses existing studies on PtH/C potentials in Europe. Particularly the situation in Austria, Denmark, France, Germany, Italy and the Netherlands is examined in detail. The analyses in these countries also attempt to identify framework conditions likely to influence the PtH/C deployment such as regulatory barriers or successful regulations. The chapter also compromises a quantitative-based approach for the estimation of PtH/C potentials in the above-mentioned countries.

Chapter VI consists of a brief summary of the report draws conclusions from previous chapters and proposes solutions and policy recommendations required to incentivise PtH/C.

# II. POWER-TO-HEAT RELATED ASPECTS OF THE EUROPEAN ENERGY SYSTEM

Heating and cooling (H/C) represents more than half of the final energy demand in Europe and thus plays an important role in reaching climate and energy targets. First subchapter II.A summarizes heating and cooling sector in general. The second subchapter II.B highlights the need for flexibility in the European electricity. The increasing share of renewable energy sources results in a higher need for flexibility in electricity system.

## II.A. Heating and cooling sector in Europe

The first subchapters give an overview of the existing European regulatory framework affecting the heating and cooling sector in general and assesses the progress in achieving the European target for H/C. Afterwards the following subchapters give an overview of the existing heating and cooling energy balances in Europe, on European and national level. Finally, different future projections on heating and cooling energy balances are demonstrated.

### II.A.1. Overview of the existing European regulatory framework

In the European Union, there is no specific legislative regulation or directive addressing the heating and cooling (H/C). The heating and cooling (H/C) sector contributes to the achievement of some of the targets formulated within the 2020 Climate and Energy package [2–4]; most important one being the share of 20% of renewable energy in final energy consumption to 2020. The heating and cooling sector also contributes to the energy efficiency target[1,2] of 20% lower energy consumption in 2020. Finally, it supports the 20% greenhouse gas emissions reductions targets in 2020, as some power generation installations are constrained in terms of their amount of greenhouse gas emissions in the European Union Emission Trading Scheme (EU-ETS). Other aspects[3] of energy policy legislation like European Ecodesign+Labelling policy for space and water heaters[4] or European building policy [6] also support energy efficiency and decarbonisation main objectives.

This section presents the elements of the existing legislative framework that have direct impacts on European power to heat and cool (PtH/C) installations, and that serve as a basis for the consolidation of policies within the 2030 horizon. The EU aims at a 40% reduction in greenhouse gas emissions compared to 1990 in 2030, together with a 27% reduction in energy efficiency compared to a business as usual scenario, and a 27% share of renewables in final energy consumption.

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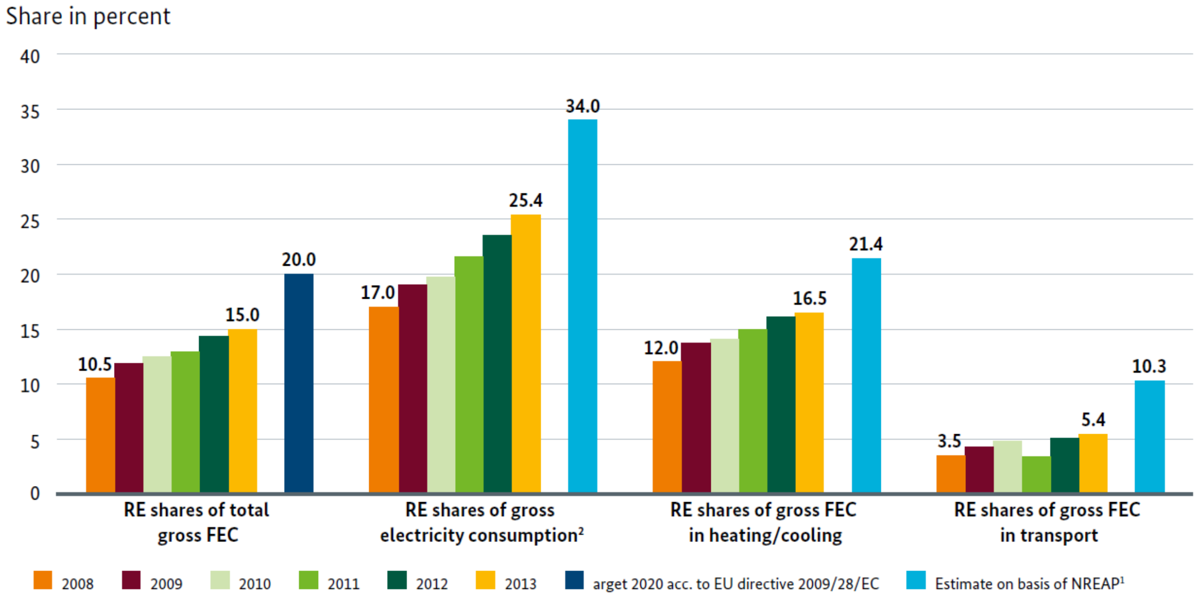
[1] Support can only be granted to cogeneration plants that save at least 10% of primary energy fuel compared to separated means of heat and electricity production (high efficiency cogeneration plants).

[2] Combined heat and power or cogeneration [5] contributes about 2% towards the 20% annual primary energy savings objective for 2020.

[3] Quantified as an EU ceiling measured in terms of primary energy or final energy consumption.

[4] Mandating efficiency ratings in the European Union.

The Renewable Energy Directive (Directive 2009/28/EC) requires each Member State to adopt a national renewable energy action plan (NREAP), setting out national targets for the share of energy from renewable energy sources consumed in transport, electricity and heating and cooling in 2020. National targets specified in National Renewable Energy Plans - NREAPs - are divided into sub targets designed for the electricity sector, the transport sector and the heating and cooling sector (RES_H/C). The share of renewables in the heating and cooling sector, based on consumed heat, is not expressed as a mandatory target as opposed to the electricity or transport sectors[5]. However, the aggregation of NREAP sets out trajectories for the share of renewables in the H/C sector for the European Union as a whole. Based on submitted NREAPs, this trajectory points towards a 21.4% share of renewables in the H/C sector, as illustrated in Figure 1. The Renewable Energy Directive also lays down sustainability criteria for biofuels used for transport and bio liquids used in other sectors[6].



1 the Energy Research Centre of the Netherlands (ECN) was commissioned by the European Environment Agency to process and evaluate the EU member states' National Renewable Energy Action Plans (NREAP). The resulting renewable energy shares for heating/cooling, electricity and transport are entered here as target values. The share for the transport sector does not match the target value defined in Directive 2009/28/EC.

2 electricity production from wind and hydropower was calculated using the normalisation rule defined in the EU Directive for the purpose of calculating the share of renewable energy in gross electricity consumption.

Sources: Eurostat [3]; ECN [31]

Figure 1: Renewable-based shares of gross final energy consumption in the electricity, heat and transport sector in the EU according to Directive 2009/28/EC [7]

Member States' progress reports show that the share of renewable energy sources in heating and cooling grew from 12% in 2010 to 16.5% in 2013 [7]. They reflect large geographical differences with countries situated in the North of Europe (Finland, Sweden, Denmark, Baltics) having shares above 35%, but countries like Austria and Slovenia having large shares (above 30%) of renewables in H/C [8].

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[5] EU transport sector target to 2020: 10% of renewables in final energy consumption.

[6] No criteria are defined in relation to solid and gaseous biomass used for electricity (such as biomass based Combined Heat and Power).

The Renewable Directive refers to the share of renewables in gross final energy consumption, meaning the “energy commodities delivered for energy purposes to industry, transport and households including public services, agricultures, forestry and fisheries”. This includes the consumption of electricity and heat by the energy branch for electricity (power plants) and heat production and including losses of electricity and heat in distribution and transmission[9, 10].

The Renewable Energy Directive [9] also requires Member States to assess the necessity to build new infrastructure for district heating and cooling infrastructure from renewable energy sources (biomass, solar, geothermal) in order to achieve the 2020 national targets. This requirement is reiterated in the Energy Efficiency Directive.

The Energy Efficiency Directive (2012/27/EU) [10] promotes specific technologies like combined heat and power (CHP) technologies, district heating and cooling, heat derived from waste treatment, or individual heating. These technologies are used in residential and commercial buildings and feature high levels of efficiency and fuel flexibility (for instance efficient district heating and cooling). In the Directive, the degree of efficiency of district heating and cooling technologies is defined based on primary energy saving targets. The Directive also improves the landmark framework for micro-CHP and requires each EU country to carry out a comprehensive assessment of its national potential of cogeneration and district heating and cooling (a main user of cogeneration) by December 2015.

The heating sector partly overlaps with the scope of the EU-ETS and partly stands within the non-ETS sector. It covers some 55 per cent of the EU's total greenhouse gas emissions. An increasing share of power to heat compared to traditional heating technologies will lead the transfer of emissions from the non-ETS sector to the ETS sector covering power generation as emitting installations.

The Directive 2003/87/CE establishing a scheme for greenhouse gas emission allowance trading within the Community - EU emission trading scheme (ETS) - covers combustion installations with rated thermal output above 20 MW [11]. It includes combined heat and power generation, but, does not include a wide range of small scale individual heating installations. Individual heating appliances in buildings emit an estimate of 600 million tonnes $CO_{2e}$ annually in the European Union.

The industrial (excluding power) and heating sector is subject to the third phase of the ETS regulation, and therefore, governed through an auctioning system based on emission benchmark and exemptions for sectors significantly exposed to risks of carbon leakage [12]. Meanwhile, electricity and heat produced in combined heat and power generation are also subject to ETS regulation, although with different rules depending on a case by case basis [13]. Outside of the EU ETS, emission mitigation in the heating and cooling sector currently derives from energy efficiency policies or fiscal policies. Looking further to 2030-2050, most of the abatement potential of the heating sector outside of the ETS derives from the building stock. An ESD Directive (Effort sharing for buildings, agriculture and waste) is being discussed. Under the ESD proposal, non-ETS emissions, – deriving from transport, buildings and agriculture – would have to be reduced by 40 per cent.

The Directive on the Energy Performance of Buildings (EPBD) [14] builds a common framework for the calculation of building performance standards, inspections and trainings of installations. One of the most prominent measures is the progress towards new built Nearly Zero-Energy Buildings (NZEB) by 2021 (or by 2019 in the case of public buildings), while in parallel supporting the transformation of existing buildings into NZEBs. The EPBD Directive supports RES-H development, but it does apply partly to the large potential for RES-H that lies in residential buildings.

Table 1: Overview of the regulations for H/C that are set at different levels

| Policy Area | Target / Policy Action Leverage |
|---|---|
| **European Union Level** | |
| **Climate Policy** | Share of total greenhouse gas reduction target |
| **Renewable Policy** | Share of electricity/heating/cooling capacity or consumption provided by district heating |
| **Renewable Policy / Building** | Energy performance requirements of building and building renovation rate |
| **Waste to Energy Policy** | Share of renewable or waste heat to be used in district heating/cooling |
| **Greenhouse Gas Emission** | Emissions allowances to combined heat and power generation (CHP) |
| **Planning/Investment framework** | Long term development plans for district heating infrastructure, CHP, Solar thermal, biomass |
| **National Level** | |
| **Renewable Policy / Building** | Energy performance requirements of building |
| **Building Policy** | Targets for replacing existing buildings and/or building renovation |
| **Waste Policy** | Share of renewable or waste heat to be used in district heating/cooling |
| | Sector targets for waste management or waste recovery |
| **Local Level** | |
| **Planning/investment framework** | Expansion of the district energy system – Target: Total number of homes |
| **Planning/investment framework** | Share of local government's energy usage in district heating/cooling – Including use of excess heat |
| **Planning/investment framework** | Interconnection of segregated district energy networks (through additional transmission pipes) |
| **Waste Policy** | Share of renewable or waste heat to be used in district heating/cooling |
| **Fiscal Policy** | Taxation |

### II.A.2. Progress in achieving the European targets affecting H/C sector

This section provides a view of the progress to the target of the share of renewables in heating and cooling. The heating and cooling (H/C) sector has been the largest contributor in terms of its share of final energy consumption in the growth of renewables [15]. This section discusses the level of progress and presents some of the barriers to policy developments.

#### *II.A.2.i Progress to date: Share of RES in heating and cooling below NREAP requirements*

According to the EU Keep on Track Project, in the RES-H/C sector, 23 Member States were above track in 2012. Similarly, in 2013, 22 Member States were on track, and only 6 Member States underachieved (Denmark, Ireland, Portugal, Slovakia, France and the Netherlands).

Analysis from the European Environment Agency reflects that growth rates witnessed in recent years are below what is required according to the NREAPs [16]. Negative deviations from the targets are being recognised in solar thermal, biomass and geothermal. In solar thermal and geothermal, none of the Member States are on track to achieve their NREAP objectives. A large number of Member States are also lagging in the share of heat pumps. Biomass has been the most progressive feedstock [17].

#### *II.A.2.ii Examples of structural barriers*

A comprehensive analysis of the barriers has been performed by the EU Keep on Track Project. In addition, one can underline the need for policy action in specific areas.

In the residential sector, where most of the potential for energy efficiency lies, renovating the existing building stock is constrained by the “Tenant-Owner dilemma” impeding the translation of energy efficiency measures into an increase in property value. In certain cases, the combination of financial incentives and prevailing market/regulatory conditions (electricity prices, grid access conditions) do not create any sufficient visibility for investors. Access to finance has often been highlighted as a barrier to policy implementation [18], especially in the most capital intensive part of the sector: in district heating, there is a need to improve access to infrastructure financing and foster energy efficiency and renewables based generation [19] in order to achieve the sector target.

At the national/local level, policy measures are mainly considered as taxation exemption together with incentives (feed in tariffs, feed in premium, low or zero interest rate loans, investment subsidies, white certificates/obligations) designed for specific installations according to technical levels (size, application) [20].

Böttger et al. [21] show that at the moment Power-to-Heat in district heating grids is not profitable for using excess electricity in Germany. State charges like the German Feed-In-Tariff, grid fees and taxes have to be paid when consuming electricity. As a result, the operation of a Power-to-Heat plant with excess electricity is not cost-efficient at the moment. In their opinion, the state charges should be revised in terms of their necessity and Power-to-Heat facilities should be exempted from the laws.

Similarly, Götz et al. [22] conclude that negative wholesale power prices are not sufficient for the usage of the PtH plants in Germany for heat production via the spot market at current variable costs. Nevertheless, the PtH plants are able to generate high returns with the provision of negative secondary control power. Possible exemptions from the network usage fees and the compensation of the primary energy factor are not sufficient to use the PtH systems for heat production via the spot market. Only with a total exemption of the additional costs (grid usage fees, electricity tax, FIT surcharge, the compensation of the primary energy factor etc.) would PtH plants be used for heat production. Nevertheless, a wide exemption from state charges should be discussed and considered due to the superior importance of PtH for the entire system.

Ehrlich et al. [23] showed that in spite of a great technical demand potential, the likely financial benefits of PtH hybrid systems at household level will continue to be small, if no governmental intervention is made to reduce the price of electricity used for heating purposes significantly. A similar conclusion is drawn by CE Delft [24], which indicates a highly constrained investment potential for Power-to-Heat applications in the current Dutch context and market outlook, but only if stronger electricity price reductions occur or if transmission tariffs are restructured.

Another crucial element which may influence the success of PtH/C applications is an adequate grid connection. CE Delft in [24] distinguishes between projects where a new grid connection is required to accommodate Power to Heat, and projects with adequate grid connections in place already. The report indicated that by 2023 some 500 $MW_{th}$ of Power-to-Heat capacity may be profitably deployed in combination with gas-fired boilers in the Netherlands, but much higher levels of profitable deployment should be expected if Power-to-Heat is employed at sites where grid connection is sufficient, e.g. combined with existing Combined-heat-and-power installations, in which case investment costs for Power-to-Heat are reduced substantially. PtH/C applications seem to have the sufficient technical maturity and potential to play a role in future European energy markets. However, many assessments identify the current policy framework, in particular electricity fees and tariffs, a key element which affect its development.

### II.A.3. Current H/C balances in Europe

Complete energy balances for primary and final energy carriers for EU Member States and acceding or candidate states are available in the database of Eurostat. Eurostat provides more than 100 different products for up to 650 categories in its balances, but little information is available on the heating and cooling sector.

The project Odyssee [25] aims to monitor energy efficiency trends in Europe and gathers indicators on energy efficiency, $CO_2$ emissions, as well as detailed data on energy consumption. In the residential sector, Odyssee data for heating/cooling (H/C) comprises final consumption for space heating, water heating, space cooling and cooking. However, not all end-use data are available either for all countries or for all years. Eurostat and Odyssee data for final energy consumption for 2013 in EU28 by sector and also by end-use for households in Odyssee data can be found in Table 2. Comparing the final energy consumption in these two databases reveals deviations on a EU28 level.

Table 2: Eurostat and Odyssee data for EU28 final energy consumption in 2013

| EU28 | Eurostat | Odyssee |
|---|---|---|
| Final Energy Consumption (TWh) | **12,870** | **12,810** |
| **Industry** | **3,241** | **3,189** |
| **Households** | **3,468** | **3,439** |
| for space heating | | 2,326 |
| for water heating | | 441 |
| for cooking | | 163 |
| for space cooling | | n.a. |
| electricity for appliances and lighting | | 494 |
| **Services** | **1,814** | **1,858** |
| **Agriculture** | **297** | **272** |
| **Transport** | **4,050** | **4,051** |

* Eurostat balances are provided in ktoe, but are converted to TWh for comparison.
** Eurostat data for 'Services' and 'Other' sector are summed in the 'Services' category.

Official national and EU statistics provide an incomplete picture regarding H/C. Data is often scattered, incomplete or not available.

The study “Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables)” [1] gives a comprehensive picture of the current state of the EU’s H/C sector as well as possible future trajectories until 2020 and 2030. The status-quo of energy demand for heating and cooling in the European countries in the year 2012 was assessed, providing a European end-use energy balance for heating and cooling. In the study, national and EU statistical data were assessed and a methodology was developed to fill data gaps in order to derive end-use balances for heating and cooling. End-use balances show final energy consumption for different applications in the industry, household and tertiary sectors which include space heating/cooling, process heating/cooling, water heating and cooking. Thirteen individual energy carriers[7] were distinguished (natural gas, coal, fuel oil, other fossil fuels, nuclear, biomass[8], RES-E, waste RES, waste non-RES, solar energy, ambient heat, geothermal, and other RES). These comprise the main fossil as well as the main renewable energy sources. The main results for heating and cooling balance are shown in Table 3.

In 2012, about 8,000 TWh of primary energy demand were used in the EU28 for H/C purposes. Thereof 45% was natural gas which is the individual most important energy carrier for the H/C supply in the EU28. Splitting up the final energy demand for H/C by energy carrier also reveals the huge importance of natural gas. Other energy carriers are relatively equally distributed, both in primary and final energy demand.

Overall, final energy demand in the EU28 accounted for about 12,821 TWh in 2012. Thereof around 6,500 TWh were used for heating and cooling (H/C) purposes, of which the most relevant is space heating with a share of 52%. Comparison of final energy demand in 2012 (presented in Table 3) and final energy demand in 2013 (according to Eurostat and Odyssee) does not reveal substantial differences, therefore data from this study can be used to describe current H/C balances. The allocation of energy carriers to

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[7] Each energy carrier used is calculated as an aggregate of one or more energy carriers from Eurostat.
[8] Biomass includes all forms of biomass (not only solid biomass).

the sectors confirms natural gas as the most dominant in each sector, especially in the tertiary sector with a 50% share.

Table 3 also shows the allocation of end-uses to the sectors residential, industry and tertiary. H/C demand in the residential sector is dominated by space heating with a share of 78%, while water heating has a substantial share of 16%. The remaining end-uses cooking and space cooling account for only 6 and 1%, respectively. In industry, process heating makes up for the major share with about 82%. Also in the tertiary sector, space heating has the major share (61%), but other end-uses such as water heating, (14%), process cooling (10%) and space cooling (9%) also show relevant shares.

Table 3: EU28 Heating and cooling balance in 2012 (based on [1])

| **Final energy demand (TWh)** | 12,821 | | |
|---|---|---|---|
| **Final energy demand for H/C (TWh)** | **6,497** | | |
| **Final energy demand for H/C by energy carrier** | | | |
| Share of natural gas (%) | 45 | | |
| Share of coal (%) | 9 | | |
| Share of biomass (%) | 12 | | |
| Share of fuel oil (%) | 12 | | |
| Share of electricity (%) | 12 | | |
| Share of district heating (%) | 8 | | |
| Share of other sources* (%) | 2 | | |
| **Final energy demand for H/C by end-use** | | | |
| Share of space heating (%) | 52 | | |
| Share of process heating (%) | 30 | | |
| Share of water heating (%) | 10 | | |
| Share of cooking (%) | 3 | | |
| Share of process cooling (%) | 3 | | |
| Share of space cooling (%) | 2 | | |
| **Final energy demand for H/C by sector (TWh)** | **Residential** | **Industry** | **Tertiary** |
| | **~ 3,030** | **2,365** | **~ 1,100** |
| **Final energy demand for H/C by energy carrier and sector** | | | |
| Share of natural gas (%) | 42 | 39 | 50 |
| Share of coal (%) | 4 | 17 | 1 |
| Share of biomass (%) | 16 | 9 | 3 |
| Share of fuel oil (%) | 12 | 9 | 15 |
| Share of electricity (%) | 11 | 7 | 27 |
| Share of district heating (%) | 9 | 8 | 3 |
| Share of other fossil fuels (%) | 2 | 10 | 0 |
| Share of other sources* (%) | 4 | 1 | 1 |
| **Final energy demand for H/C by end-use and sector** | | | |
| Share of space heating (%) | 77 | 15 | 61 |
| Share of process heating (%) | | 82 | 6 |
| Share of water heating (%) | 16 | | 14 |
| Share of cooking (%) | 6 | | |
| Share of process cooling (%) | | 3 | 10 |
| Share of space cooling (%) | 1 | | 9 |

* Other sources include other RES like solar (thermal) energy, ambient heat and geothermal energy.

The breakdown of energy carriers by H/C end-use is illustrated in Figure 2. There are substantial variations across energy carriers and H/C end-uses. Still, for most end-uses natural gas is the dominant energy carrier, except for cooling.

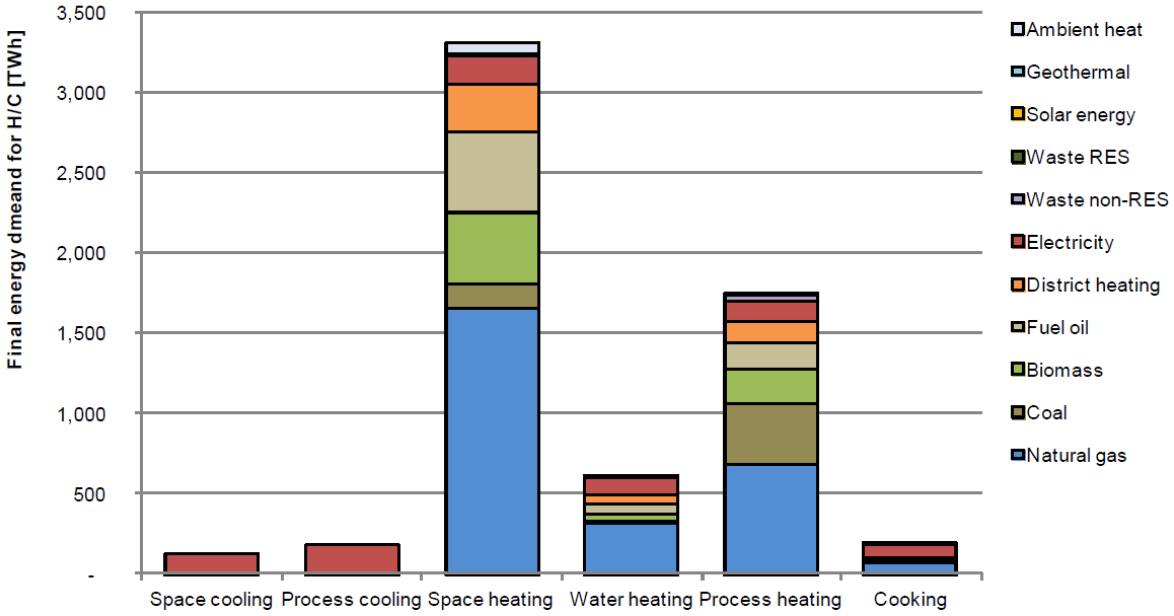


Figure 2: Final energy demand for EU28 by end-use and energy carrier [1]

### II.A.4. Current national H/C balances

In the following section, H/C demand is compared across countries and sectors in each country. Included are EU28 Member States plus Norway, Switzerland and Iceland.

While the total EU28 the energy demand for H/C equals about 51% of the total final energy demand in 2012, this share deviates substantially across countries. The share ranges between 36% in Norway and Portugal to an exceptionally high value of 68% in Slovakia. The values are on the one side mainly influenced by the presence of energy intensive industry and space heating demands, but also by the importance of energy demand in non-H/C sectors, mainly transport.

A comparison of final energy demand for H/C by end-use is illustrated in Figure 3. Notable differences can be observed. For instance, the share of process heating varies from about 15% in Estonia to 56% in Portugal. Although space cooling shows clear peaks in Mediterranean countries, its share arrives at a maximum of 9% (Greece) of total final energy demand for H/C – excluding the southern and very small Member States Malta and Cyprus where space cooling makes up 19% and 33%, respectively. Process cooling, on the other hand, is more evenly distributed across countries. Despite these differences, generally, space heating and process heating account for the major share of H/C use in most countries.

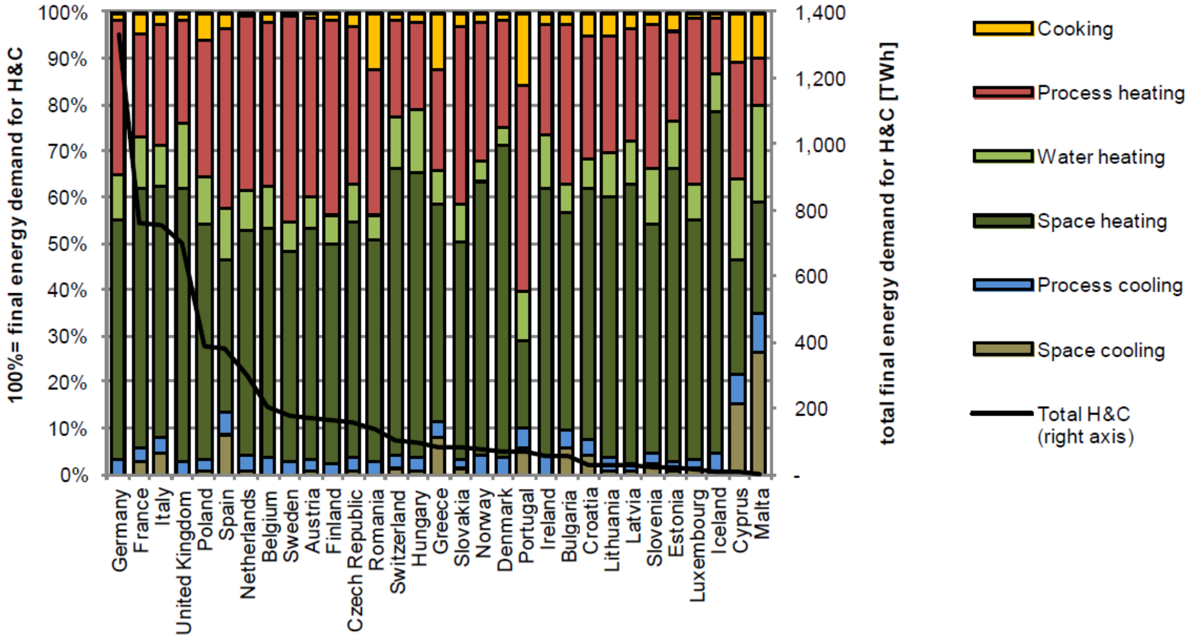


Figure 3: Final energy demand for H/C in the EU28+3 countries by end-use [1]

When looking at the individual energy carriers used to provide H/C, this is a lot more diverse as illustrated in Figure 4. The countries shown are sorted according to their total final energy demand for H/C in 2012, starting with the largest consumer, Germany, on the left. Natural gas is the major energy carrier for H/C in many countries, especially in the United Kingdom, Germany, Netherlands and Hungary. Countries with a natural gas share of below 5% are the Nordic countries Finland, Sweden, Norway and Iceland plus Malta and Cyprus. Poland is the country with an exceptionally high share of coal, followed by Slovakia and the Czech Republic. District heating has particularly high shares in northern and eastern countries – Lithuania, Estonia and Denmark. Electricity has high shares of above 20% in Norway and Iceland and in countries with high space cooling demand, which are mainly the Mediterranean countries. The proportions of renewable energy sources (RES) to some extent reflect the natural resources of the respective countries. In Sweden and Finland the share of biomass is quite high compared to the EU average. Cyprus on the other hand has a high share of solar energy and Iceland is the only major user of geothermal energy.

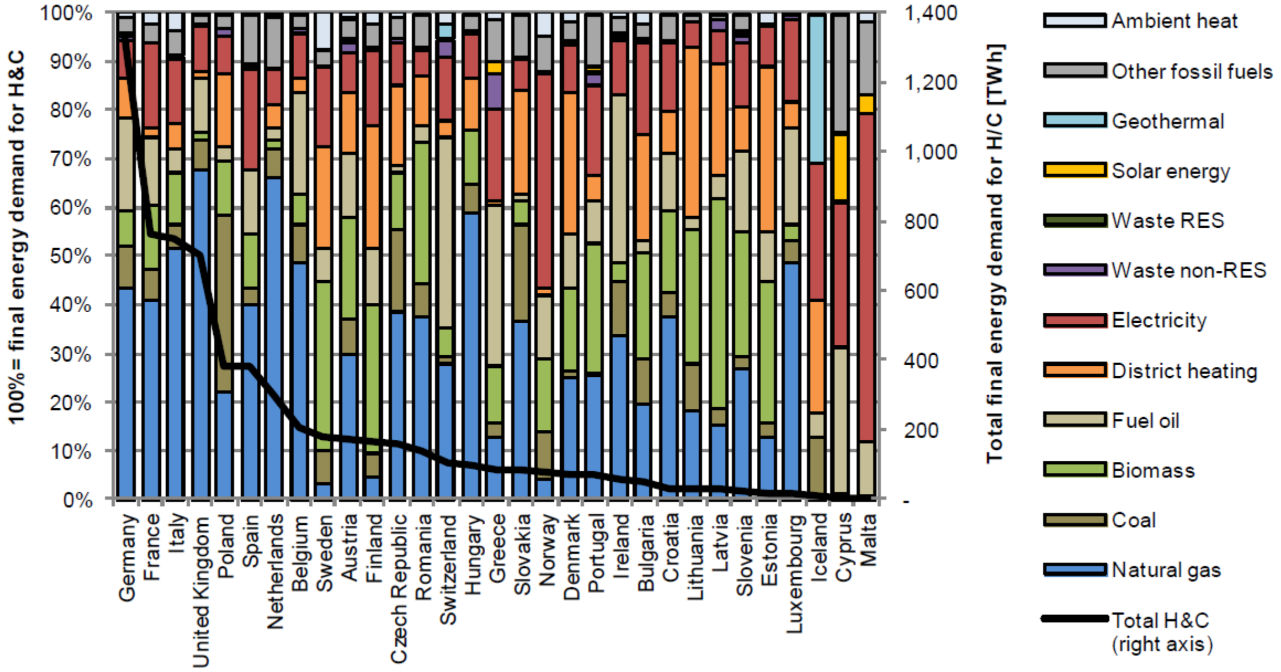


Figure 4: Final energy demand for H/C in the EU28+3 countries by energy carrier [1]

### II.A.4.i Industry sector

The distribution of individual H/C end-uses in industry across the European countries (Figure 5) is mainly influenced by differences in the industrial structure. Countries with higher shares of basic industries (iron and steel, non-metallic minerals) principally have higher shares of a demand for high temperature process heat, whereas countries with more light industries (transport, machinery) tend to have higher shares of space heating. Still there are some common patterns, for example, process heating is an important end-use in all countries, even for temperatures above 500°C, while process and space cooling only accounts for a smaller share in all countries.

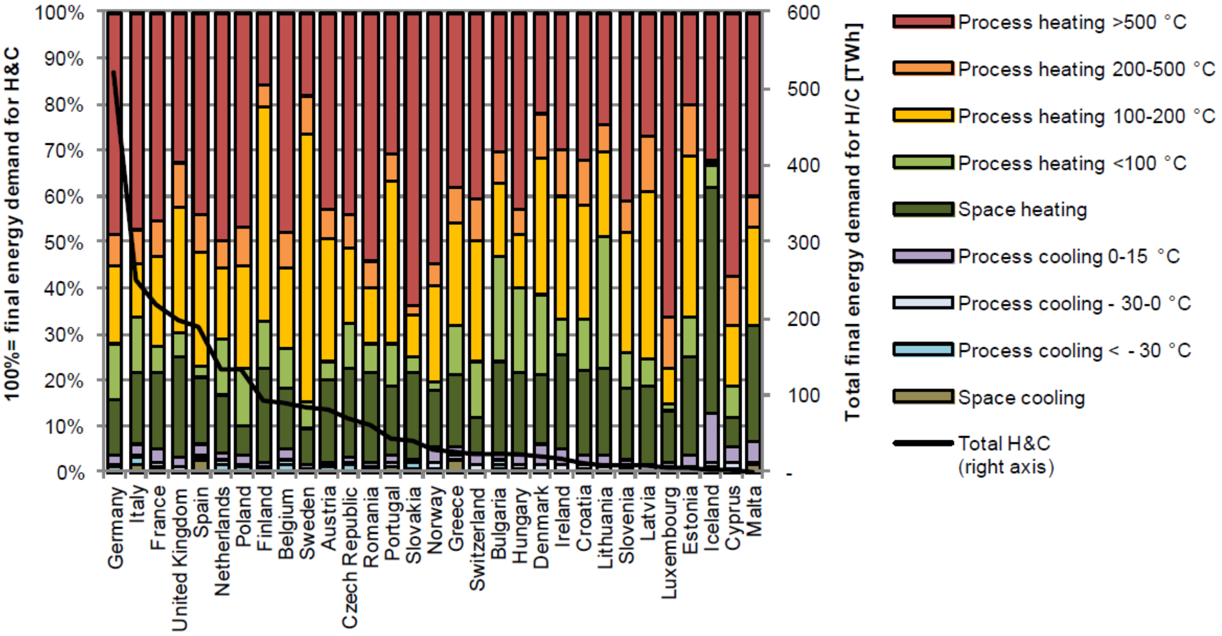


Figure 5: Share of H/C end-uses in the industry sector per country [1]

### II.A.4.ii Residential sector

The most important sector for H/C is the residential sector and the most important end-use is space heating – it is the category with the highest share of total H/C demand.

Figure 6 compares the shares of H/C end-uses in the residential sector. Most of the countries show a similar distribution on energy demand on end-use categories. However, there are some differences. For example, in Cyprus and Malta the energy demand for water heating and space cooling dominates, while Portugal exhibits a very high share of the final energy demand for cooking. In almost all countries, space heating is the dominant end-use category.

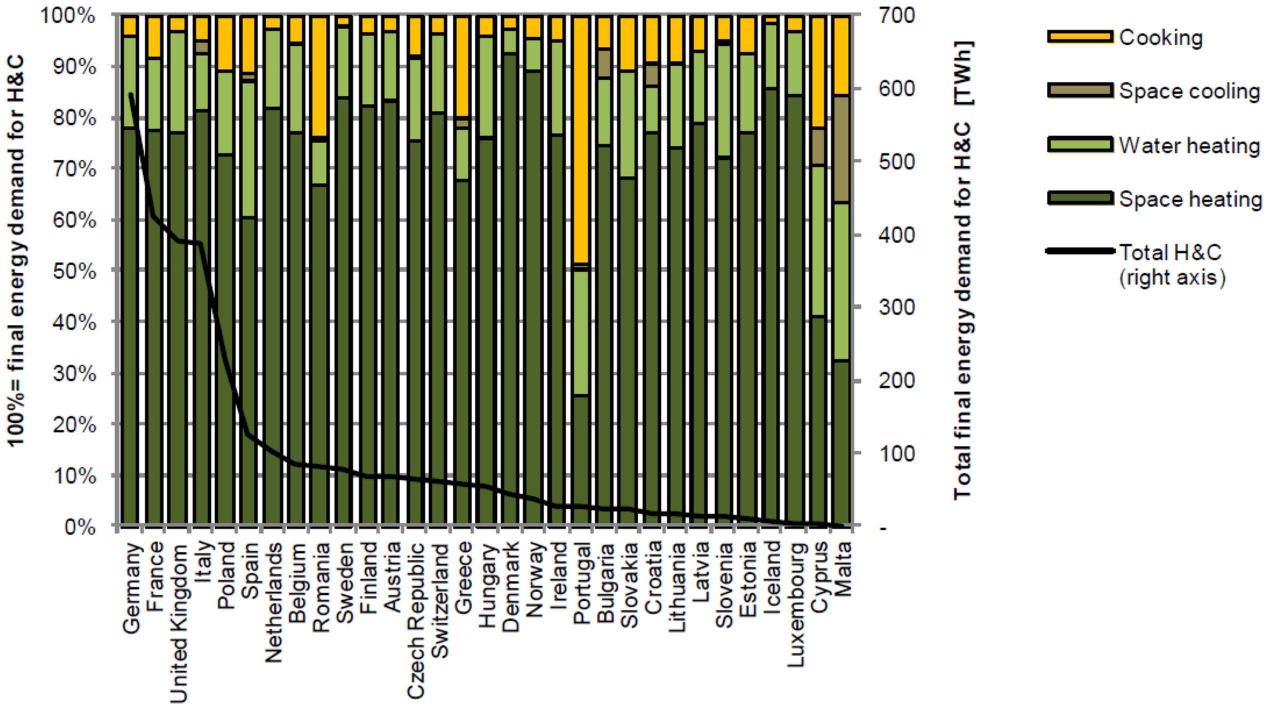


Figure 6: Share of H/C end-uses in the residential sector per country [1]

### *II.A.4.iii Tertiary sector*

The shares of H/C end-uses on a country level in the tertiary sector are compared in the Figure 7. Similar as in the residential sector, climatic differences can be distinguished regarding H/C.

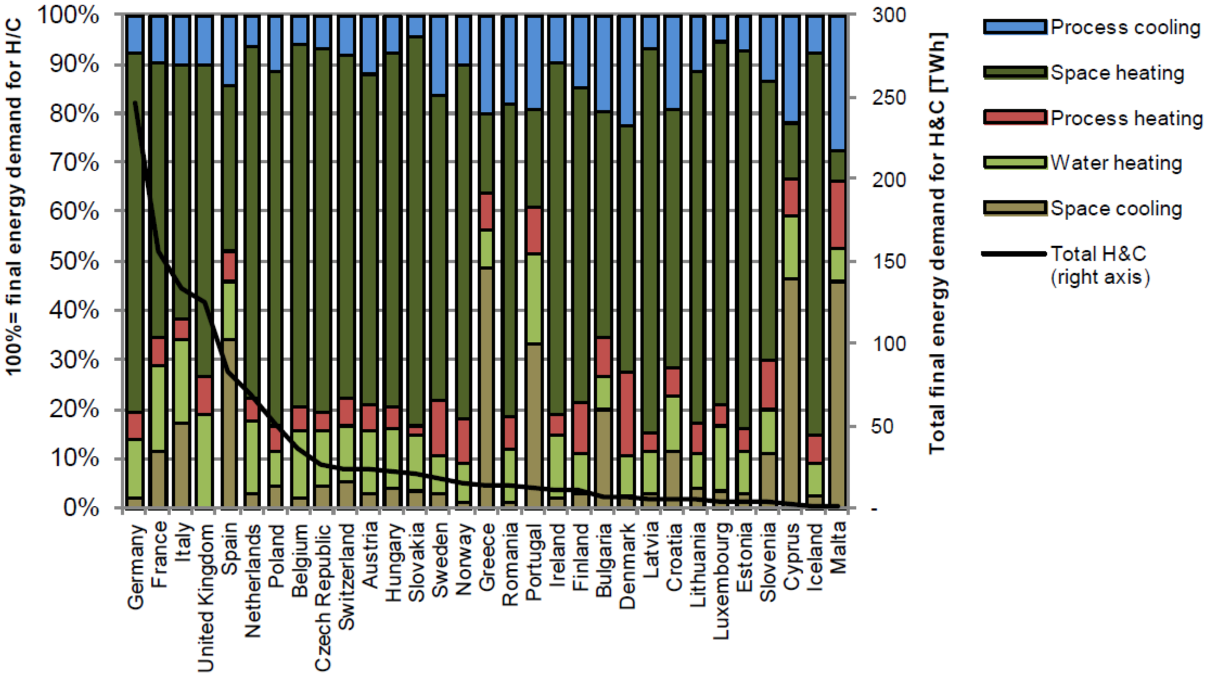
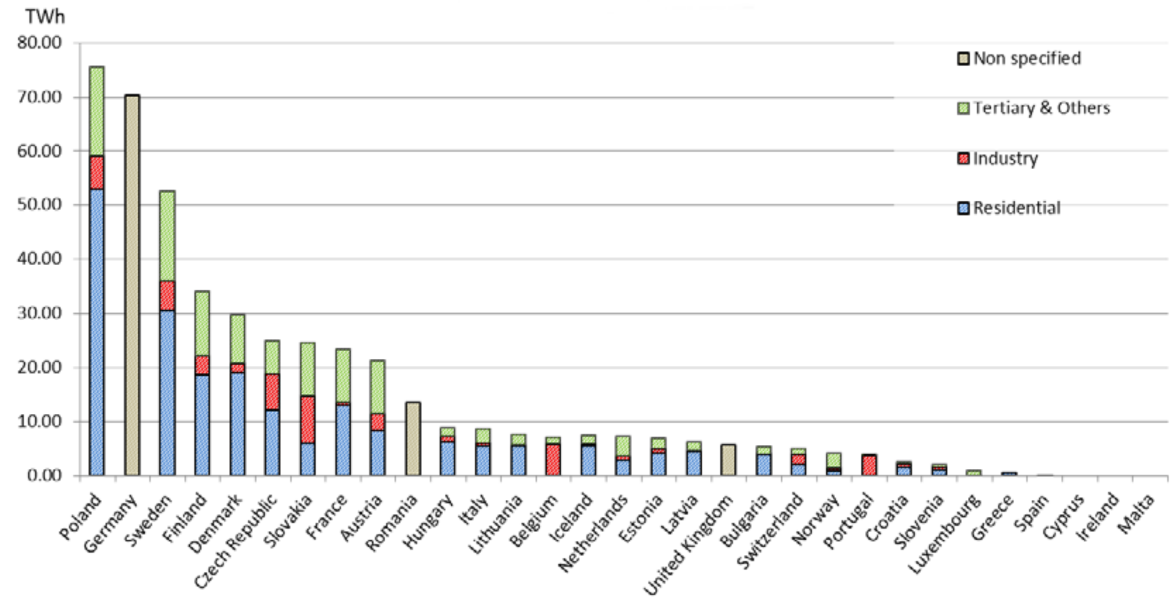


Figure 7: Share of H/C end-uses in the tertiary sector per country [1]

### II.A.4.iv District heating and cooling

Study [1] provides also in depth analysis of district heating and cooling (DHC).

As can be seen in Figure 8, Poland, Germany, Sweden and Finland are the countries with the highest heat sales from district heating and together they represent around half of total district heat sales in the considered countries. District heat is used mainly in the residential sector (45%) and the tertiary sector (24%), while only 11% is in the industry sector. Approximately 20% of the final consumption is used in not specified sectors. The penetration of district heating in the residential sector is highest in Iceland, but Iceland has a unique energy supply for district heating, with 97% of the heat coming from geothermal sources and the rest from renewable electricity.



nc = non comparable

Figure 8: District heating final consumption per country [1]

The district cooling sales for 2012 are presented in Figure 9. District cooling (DC) is still not a widespread technology and many countries lack DC systems, but statistics regarding district cooling are also much less detailed than those for district heating. The highest district cooling sales were registered in Sweden and France.

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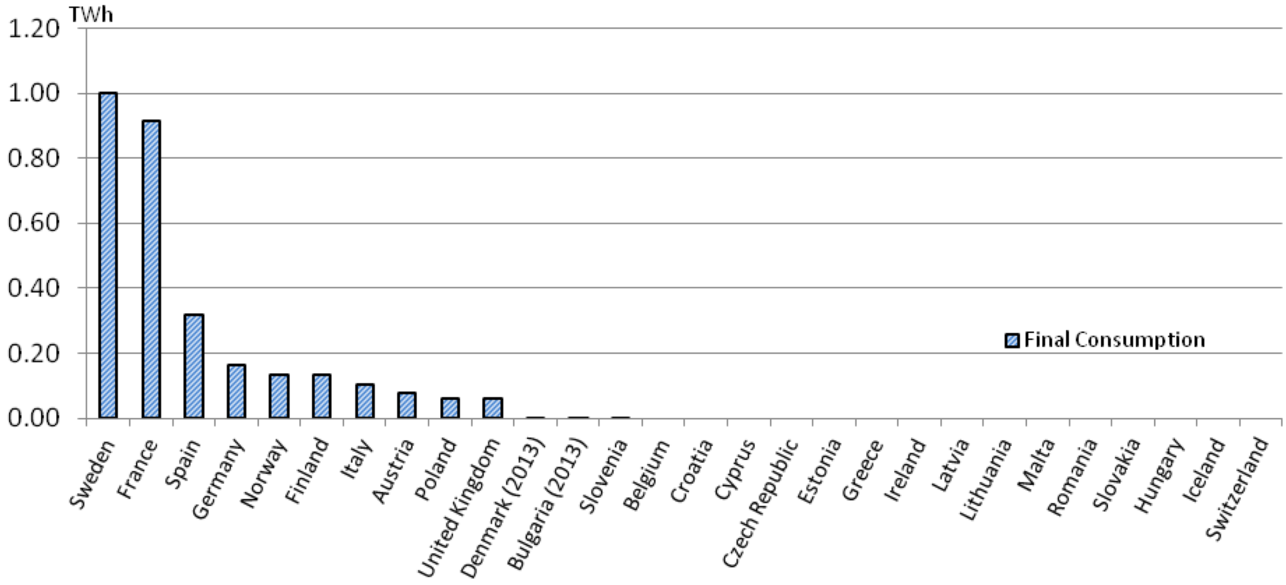


Figure 9: District cooling final consumption per country [1]

## II.A.5. Projections of H/C demand in the EU28

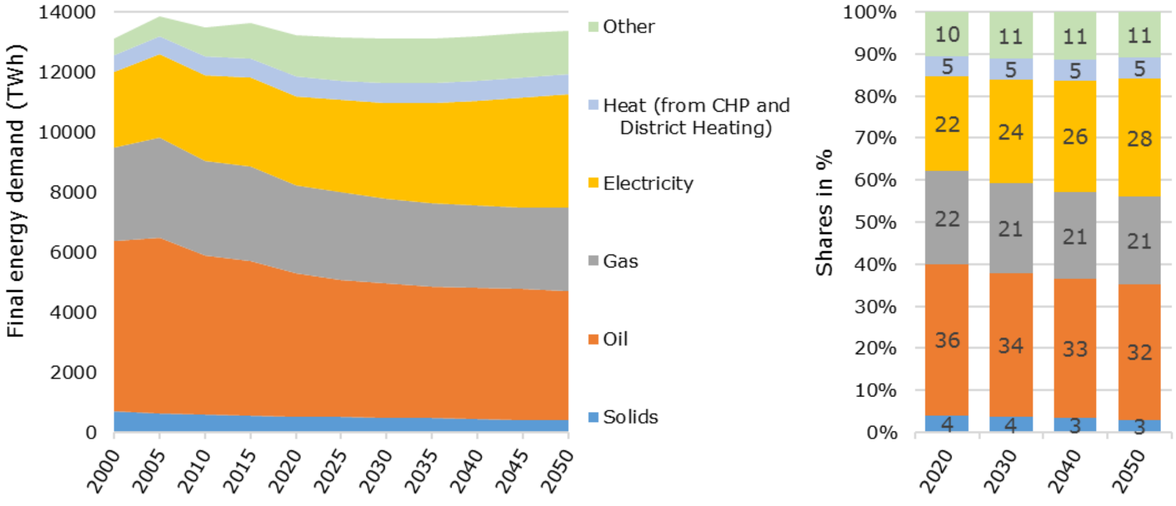
The Potential development and future prospects of the heating and cooling sector are based on the “2013 EU Reference scenario: EU energy, transport and GHG emissions trends to 2050” [26][9]. The EU reference scenario shows likely trends of all sectors and for all EU28 Member States.

This Reference scenario is based on the latest available statistical year from Eurostat at the time of the modelling (2010). Reference scenario includes policies and measures adopted in the Member States by April 2012 and policies, measures and legislative provisions adopted by or agreed in the first half of 2012 at EU level (including the Energy Efficiency Directive). A consortium led by the National Technical University of Athens elaborated the Reference scenario, using the PRIMES model for the projections.

In this section, the main results of the Reference scenario 2013 are presented, notably for energy demand for the EU28 and per country.

Expected trends in final energy demand are illustrated in Figure 10 and Figure 11, showing accelerating energy efficiency improvements, in particular until 2020. Beyond 2030, in the absence of additional policies on efficiency, final energy consumption follows an increasing pace, although slow. In addition to the considerable energy savings, the projection also indicates a switch in the fuel mix of final energy consumption over time, in favour of renewable energy forms and electricity.

The Current H/C balance presented in previous chapter shows that final energy demand in the EU28 accounted for 12,821 TWh in 2012, which is slightly lower than the level of final energy demand between 2010 and 2015 according to the EU Reference scenario. In the Reference scenario total EU28 final energy demand accounts for 13,463 TWh in 2010 and 13,620 TWh in 2015.



* ‘Other’ includes renewable energy forms and other fuels as hydrogen and ethanol

Figure 10: Trends in EU28 final energy demand by energy carrier (based on [26])

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[9] During the preparation of this report, a new version of Reference scenario was published.

In the final energy demand, electrification is a persistent trend (Figure 10), mainly as a result of a shift towards electricity for heating and cooling and a continued increase of electric appliances in the residential and the tertiary sector. Gas maintains its role in the final energy demand, but other fossil fuels see their share decrease.

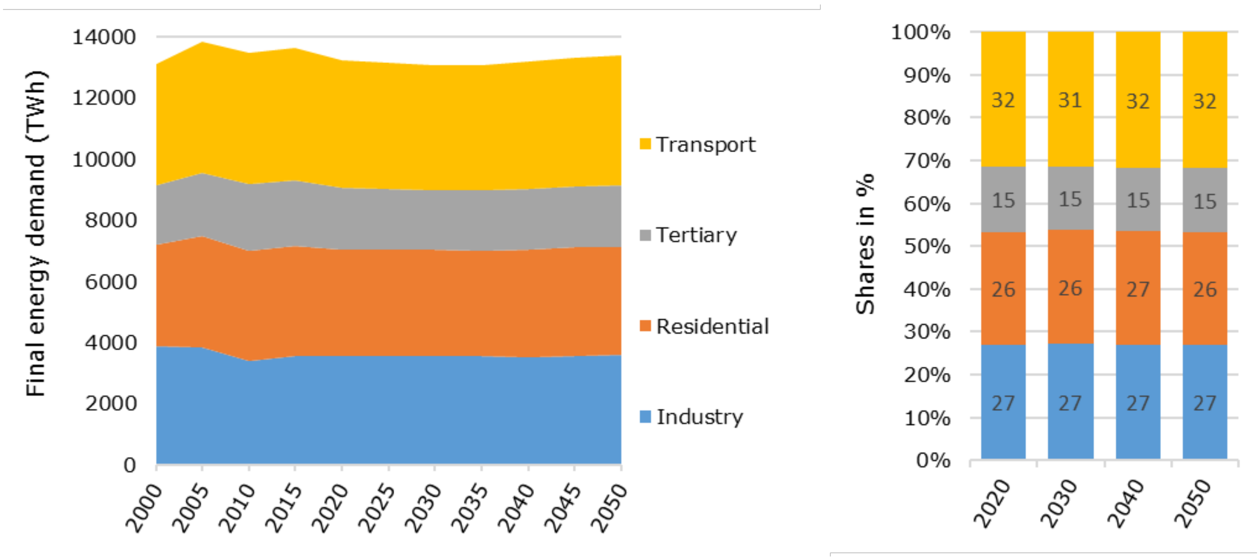

Figure 11: Trends in EU28 final energy demand by sector (based on [26])

The distribution of final energy consumption across sectors (Figure 11) remains broadly similar to the current picture, all the way to 2050. The residential sector comprises 26% of final energy consumption in 2030. The share of industry and tertiary sectors remains the same throughout the projection period, 27% and 15%, respectively. Transport sector continues to have the highest share in final energy consumption (31% in 2030).

### *II.A.5.i Possible projections for H/C sector*

As well as the issue that current energy balances not providing a complete picture for H/C, there is also insufficient data for potential development of the H/C sector.

According to the EU reference scenario [26] the final energy demand in the EU28 is expected to amount to 13,090 TWh in 2030 and 13,383 TWh in 2050, which is not a significant change compared to 12,821 TWh in 2012.

The distribution of final energy consumption across sectors remains broadly similar to the current picture, all the way to 2050. The residential sector comprises 26% of final energy consumption, industry 27% and tertiary sector 15% both in 2030 and 2050. The transport sector has a 31% share in final energy consumption in 2030, and 32% in 2050. Projections by energy use for residential and the tertiary sector provide data on the H/C sector, which show reduction in final energy demand for H/C purposes. The EU reference scenario does not provide projections for industry by end-use so data presented in Table 4 is an estimate based on the current balance presented in section II.A.1.

Table 4: EU28 H/C sector projection for 2030 (based on [1] and [26])

| | Residential | Industry | Tertiary |
|---|---|---|---|
| **Final energy demand by sector (TWh)** | **3,458** | **3,570** | **1,946** |
| **Final energy demand for H/C by sector (TWh)** | **2,836** | **2,365** | **1,187** |
| **Final energy demand for H/C by end-use and sector** | | | |
| Share of heating (%) | 73 | 97 | 56 |
| Share of water heating (%) | 16 | | |
| Share of cooking (%) | 9 | | |
| Share of cooling (%) | 2 | 3 | 16 |
| Share of other heat uses (%) | | | 28 |

* Other heat uses refer to other heat uses for which a specific share could not be determined.

For the purposes of creating the 2030 Energy and Climate Framework [27] and the Energy Efficiency Review Communication [28] several scenarios for H/C sector were developed. The same scenarios were used when the document ' Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy for Heating and Cooling' [29] was created. By reviewing the mentioned documents, it is possible to derive three main scenarios reflecting the future needs on heating and cooling on an EU level. The scenarios can be divided as follows:

- The 2013 Reference scenario (REF 13): scenario includes all policies relevant to the H/C sector adopted by Member States by Spring 2012
- The EE27 policy scenario (EE 27): this scenario assumes RES and EE shares of 27.8% and 27% by 2030, respectively. Moreover, GHGs should be reduced by 40.2% by 2030 and 78.8% by 2050 as compared to 1990
- The GHG40RES30EE30 scenario (GHG40): In this scenario, RES and EE shares will amount to 30.3% and 30% by 2030 respectively, while GHGs will be reduced by 40.6% and 81.8% by 2030 and 2050, respectively, as compared to 1990.

The aforementioned scenarios include projections (not forecasts) for heating and cooling sectors comprising district heating systems, steam and industry as well. However, in the scope of this report, the main focus is on heat for heating and preparation of domestic hot water as well as on cooling. In that sense steam is not considered due to the fact that most of the PtH/C technologies described in the following chapters do not have the ability to generate steam.

In Figure 12 an overview of the gross final energy and heating and cooling consumption in the scenarios being observed is presented. It can be noticed that the 2013 Reference scenario assumes relatively stable consumption of gross energy as well as consumption of energy for heating and cooling. The remaining two scenarios indicate that gross energy consumption as well as heating and cooling decrease by 2050. More specifically, at the EU level gross final energy decreases by 22% (EE27) to 33% (GHG40) from 2010 until 2050. In that sense, heating and cooling will participate a lot in achieving these goals – demand needs to be reduced by 42% (EE27) to 56% (GHG40) by 2050.

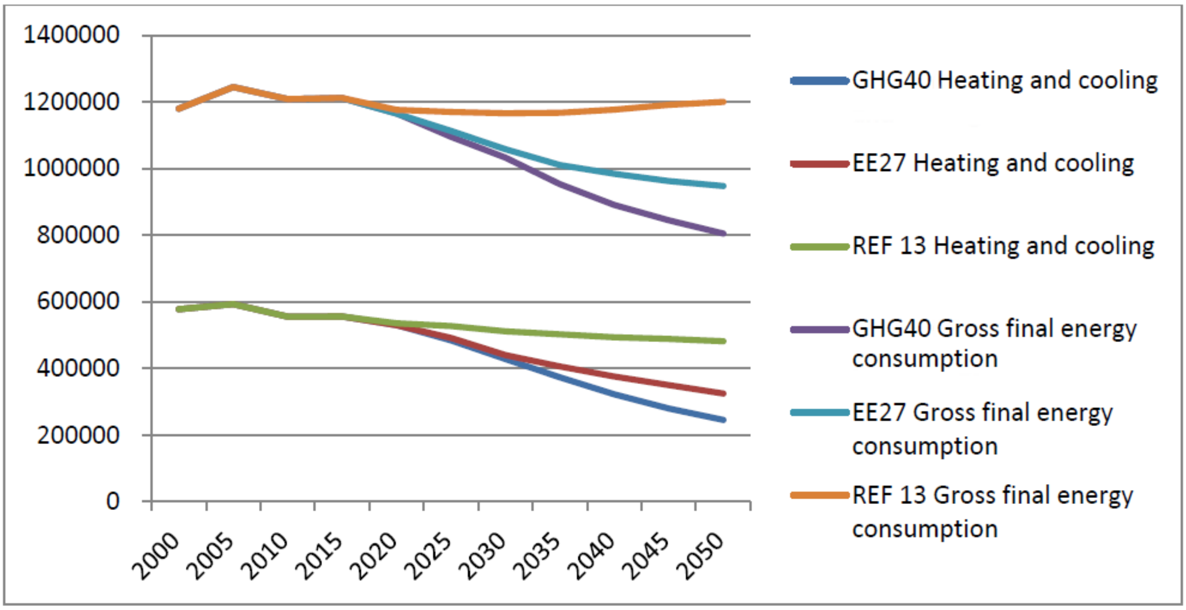

Figure 12: Gross final energy and heating and cooling consumption (ktoe) across scenarios[29]

If PtH/C is considered as a way to provide additional system flexibility in order to support stronger integration of intermittent renewable energy sources then the residential sector should be taken into account as a key factor. Namely, PtH/C technologies should be deployed in order to satisfy heating and cooling demands primary for residential sector due to their technical features, as will be elaborated later. However, it is of particular importance to have insight on projections of heating and cooling demands. In that sense Figure 13 depicts demands on heating and cooling by 2050 in the residential sector for all three observed scenarios. Energy demand for heating will decrease by 20% and 30% by 2050 according to EE27 and the GHG40 scenario, respectively. In the case of cooling demand, the 2013 Reference scenario implies the greatest increase for cooling against to GHG40 scenario. In any case, it can be concluded that heat demand decreases in all scenarios, while cooling demands significantly increase.

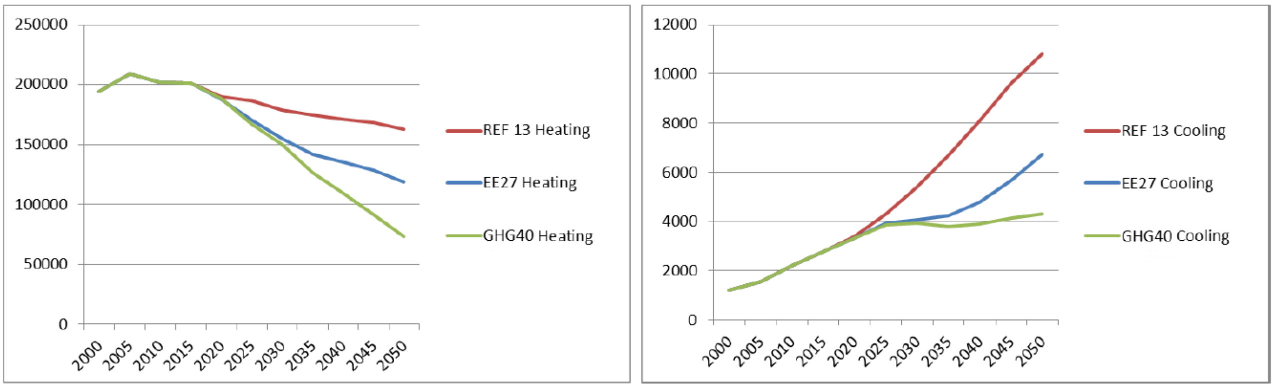

Figure 13: Final Energy per energy use (ktoe) residential heating (left) and cooling (right) demand [29]

More detailed analysis is given in Figure 14 where heating and cooling demand are divided into water heating and cooking. Naturally, heat demand for cooking is not of particular importance in the sense of PtH/C deployment.

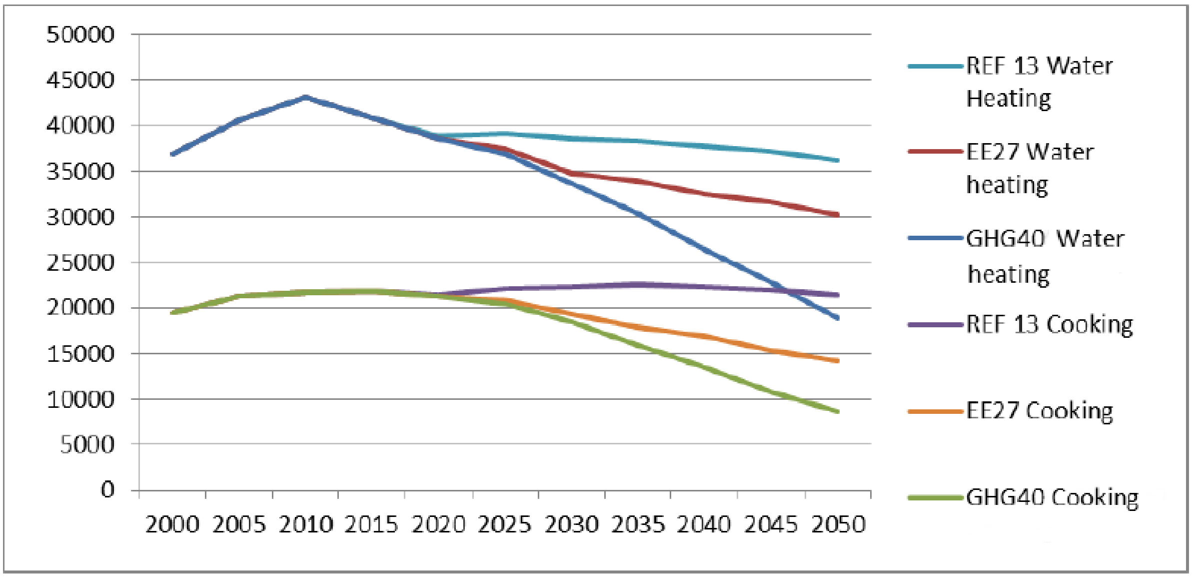

Figure 14: Final Energy per energy use (ktoe) Other Heat Uses: Water Heating and Cooking[29]

The presented possible future heat and cool demand indicates a theoretical maximum potential for PtH/C technologies providing heat for final energy consumption. However, the technical and economic potential depends on the required flexibility of the power system. Following chapter provides insights for the required flexibility in the European electricity system.

## II.B. Flexibility in the electricity system

### II.B.1. Country specific assessment of renewable development and impacts on the electricity system

Contemporary power systems face many challenge, particularly around the integration of high shares of intermittent renewable energy sources, dominantly wind and photovoltaic. Due to the present design of electricity markets, such as intermittent renewable energy sources in general have a privileged position in the sense that power they generate is not in correlation neither with power demand, nor with price signals from the market. The power generated from renewable energy sources is delivered to the power system in any case. In that sense high shares of renewable energy sources could jeopardize the stability of the power system because of a lack of large scale storage units. However, this fact should also change until 2030.

Concerning the development of renewable energy sources, the following table gives an overview of the European Union's goal regarding the deployment and utilization of intermittent renewable energy sources to 2030. The data are obtained for wind and solar, i.e. photovoltaics from EU Reference scenario [26].

Table 5: Development of intermittent renewable energy sources on EU28 level [26]

| | EU28 | | | |
|---|---|---|---|---|
| | **2015** | **2020** | **2025** | **2030** |
| Gross electricity generation ($GWh_{el}$) | **3,416,910** | **3,428,487** | **3,530,642** | **3,664,473** |
| **Wind** | 263,506 | 487,529 | 632,113 | 768,244 |
| **Solar** | 96,144 | 142,787 | 177,015 | 206,378 |
| **Total intermittent RES** | 359,650 | 630,316 | 809,128 | 974,622 |
| **Share of intermittent RES(wind+solar) in total electricity generation** | 10.5% | 18.4% | 22.9% | 26.6% |
| Net generation capacity ($MW_{el}$) | **930,128** | **1,017,923** | **1,067,357** | **1,138,323** |
| **Wind** | 123,698 | 204,726 | 258,081 | 305,395 |
| **Solar** | 76,309 | 110,110 | 133,723 | 149,432 |
| **Total intermittent RES capacity** | 200,007 | 314,836 | 391,804 | 454,827 |
| **Share of intermittent RES (wind+solar) in total installed capacity** | 21.5% | 30.9% | 36.7% | 40.0% |

More detailed representation of electricity generated and installed capacity of renewable energy sources in EU's Member States is given in Figure 15 and Figure 16, respectively.

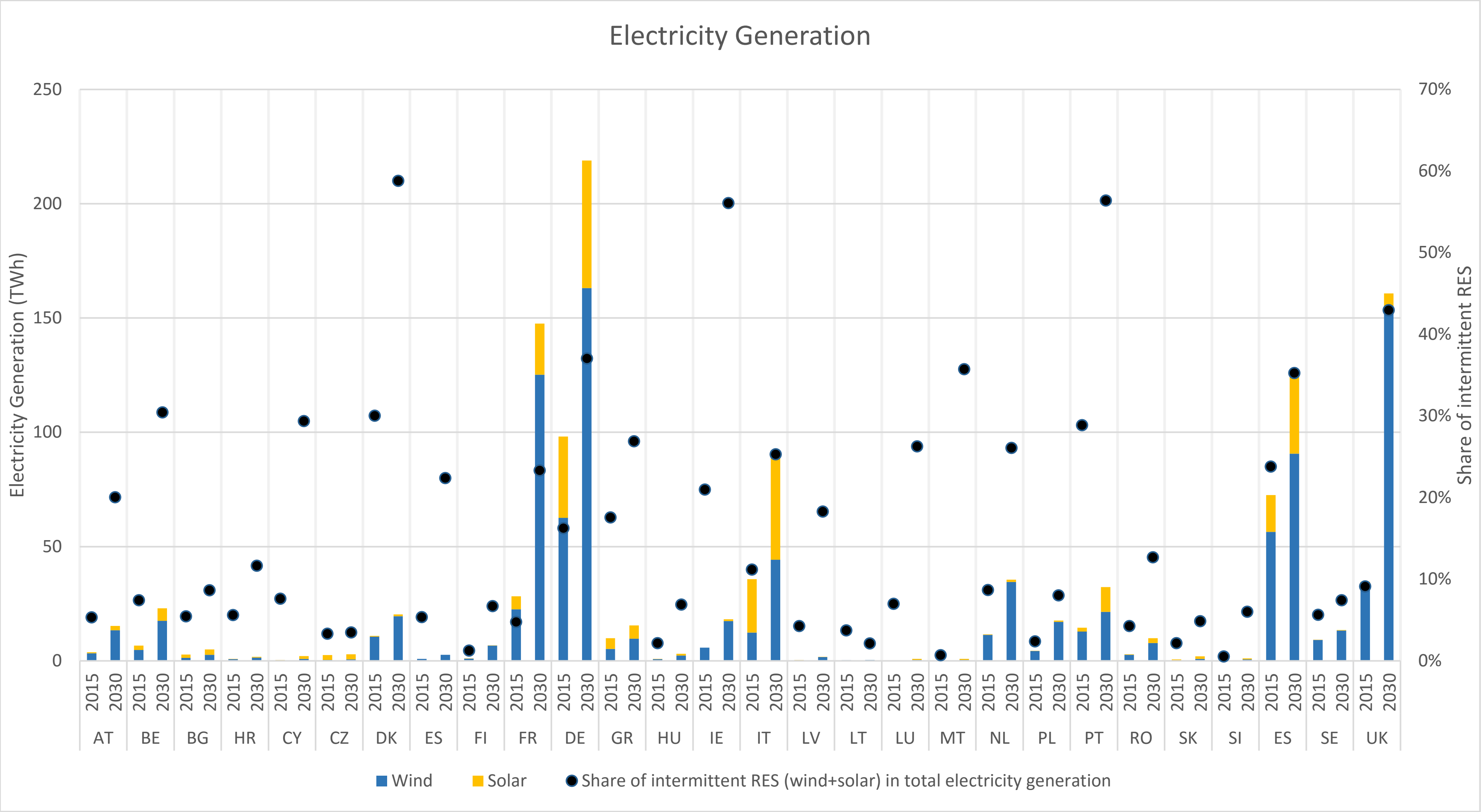

Figure 15: Electricity generation by RES (wind & solar) in EU Member States own demonstrations based on [26]

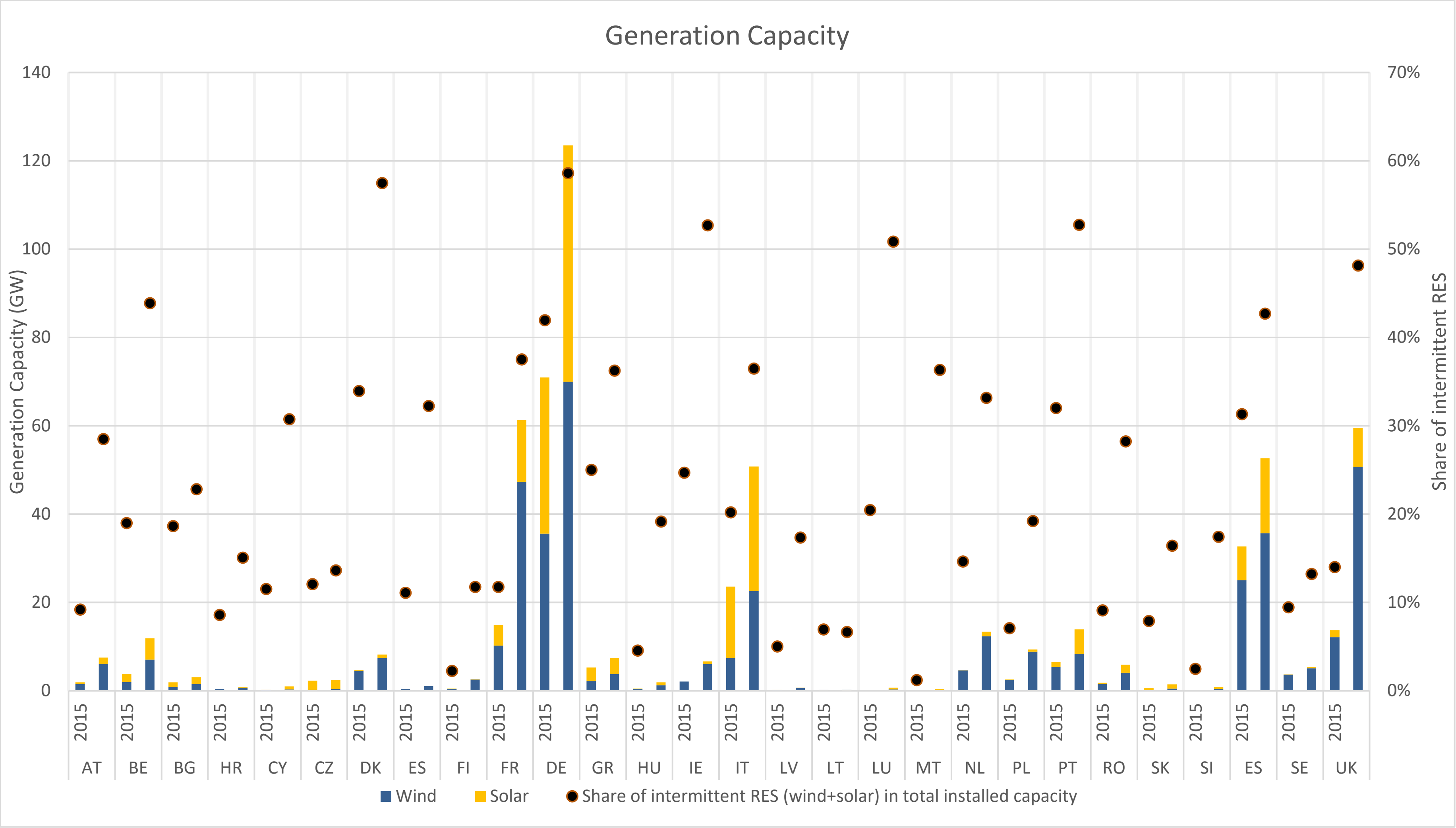

Figure 16: Generation capacity of RES (wind & solar) in EU Member States own demonstrations based on [26]

From the aforementioned data, it is possible to conclude that generation from intermittent renewable energy sources will be more than double by 2030. Such circumstances will cause additional requirements for system flexibility. Until now, the structure of the electricity demand was determining the required flexibility in the system. With a higher share of intermittent generation assets, the generation of intermittent renewable energy sources also needs to be considered for the determination of the required flexibility.

### II.B.2. Overview of existing flexibility options

The stability of the power system greatly relies on the amount of the flexibility, which can be provided to the system. Flexibility refers very often to ancillary services as an inevitable part of the modern power system. Conventional power plants fuelled by hard coal or lignite cannot provide a lot of flexibility to the power system due to their dynamic performances. Power plants based on steam turbines fuelled by gas can provide some flexibility, but still not in a greater amount. Some improvements to support the system with high share of renewable energy sources could be achieved if a minimal technical load factor of existing plant can be reduced and/or advanced operation strategies adopted. Power plants based on gas turbines (especially in open cycle) can provide flexibility to the power system. However, drawbacks of such solutions are relatively high OPEX which leads to the low capacity factor and in consequence to opportunity costs. On the other hand, gas turbines together with hydro power plants are the main source of flexibility in traditional power system. Due to the present design of the electricity market where deployment of certain power plants is determined by the so called *merit order* (Figure 17), conventional flexible power plants are losing their market share. This may lead to situations where potential investors do not make investments into these types of power plants and therefore the future power system faces certain risks regarding the maintaining flexibility and stability.

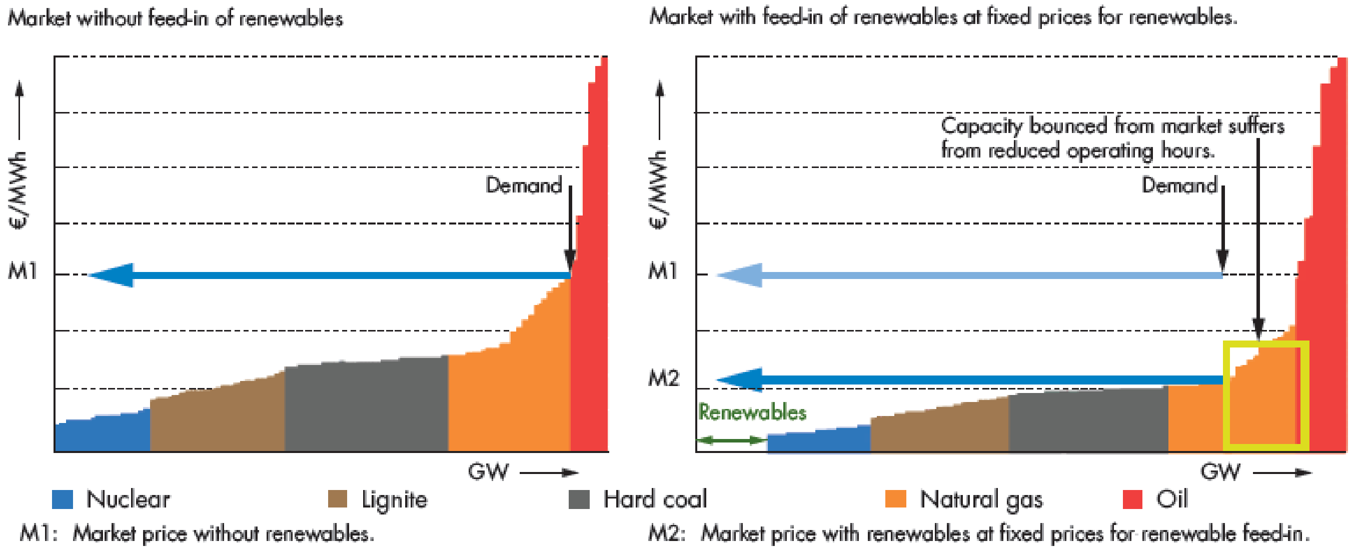

Figure 17: Merit order [29]

By taking into consideration the above mentioned parts, several potential solutions could be of utmost importance for the future power system:

- Deployment of highly flexible, fast responding generation units such as reciprocating gas engines. Such generation units can achieve capacities of several hundreds of MWs in only a few minutes (cold start). Investment cost are relatively low (about 500 EUR/kW$_{el}$). Together with the fact that efficiencies are relatively high (about 50%) such units represent a good opportunity to support the power system with increased share of renewable energy sources.
- Increase of interconnection capacities, i.e. reinforcement of the grid would enable transmission of excess renewable electricity long distances across Europe and in that way support integration of high shares of intermittent renewable energy sources. Some authors suggest that by introducing the so called centralised approach, i.e. integrated market for ancillary services, it is possible to reduce the realised amount of balancing power and energy [30]. For instance, in the case of South and South Eastern Europe it is possible to achieve a reduction of balancing capacity of approx. 50% if the power system is operated centrally i.e. on regional level [30].
- Demand Side Management should provide flexibility on the consumer side. Namely, consumers should manage their consumption according to the price signals from the energy markets. However, for such solutions it is necessary not only to develop but also deploy adequate infrastructure which will support active participation of consumers.
- Deployment of energy storage. Energy storage can provide additional flexibility to the power system. There are several types of storage technologies, such as electrical (capacitors, superconducting magnetic energy storage), thermal (ice storage, liquid air energy storage), electrochemical (batteries, flow batteries), chemical (hydrogen), mechanical (compressed air energy storage, flywheel energy storage, hydroelectric) [31]. Energy storage still does have significant role in the power system. However, this fact is starting to change and an additional challenge is to define the position of energy storage on the energy markets, should they be treated as generation assets, consumers, or something else i.e. it is necessary to derive adequate framework conditions. In [29] is emphasized that storage is a flexibility instrument that faces certain obstacles such as high storage cost, high grid access fees, immaturity of technology and control systems.

A review of literature shows many sources related to flexibility in the power system with different definitions of flexibility as well as different approaches to flexibility. However, most of them could be summarized with the definitions given in [32] where flexibility is defined *as the technical ability of a power system unit to modulate electric power feed-in to the grid and/or power out-feed from the grid over time* or as in [33] *modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterise flexibility include the amount of power modulation, the duration, the rate of change, the response time, the location etc.* It can be concluded that the flexibility is a product on a liberalized power market which is being traded as a part of ancillary services. In Figure 18 a representation of the possible flexibility options in the power system which can ensure its stability is given. The options are divided to the supply side, i.e. to the flexible generation units which are characterised with ramp rate and generation capacity adequate to provide control power and to the demand side which is further subdivided to the industrial and residential sector. Additional source of the flexibility are energy storage units which are differentiated by the availability for dispatch as well as renewable energy sources, such as wind and photovoltaic whose generation theoretically can be curtailed if needed.

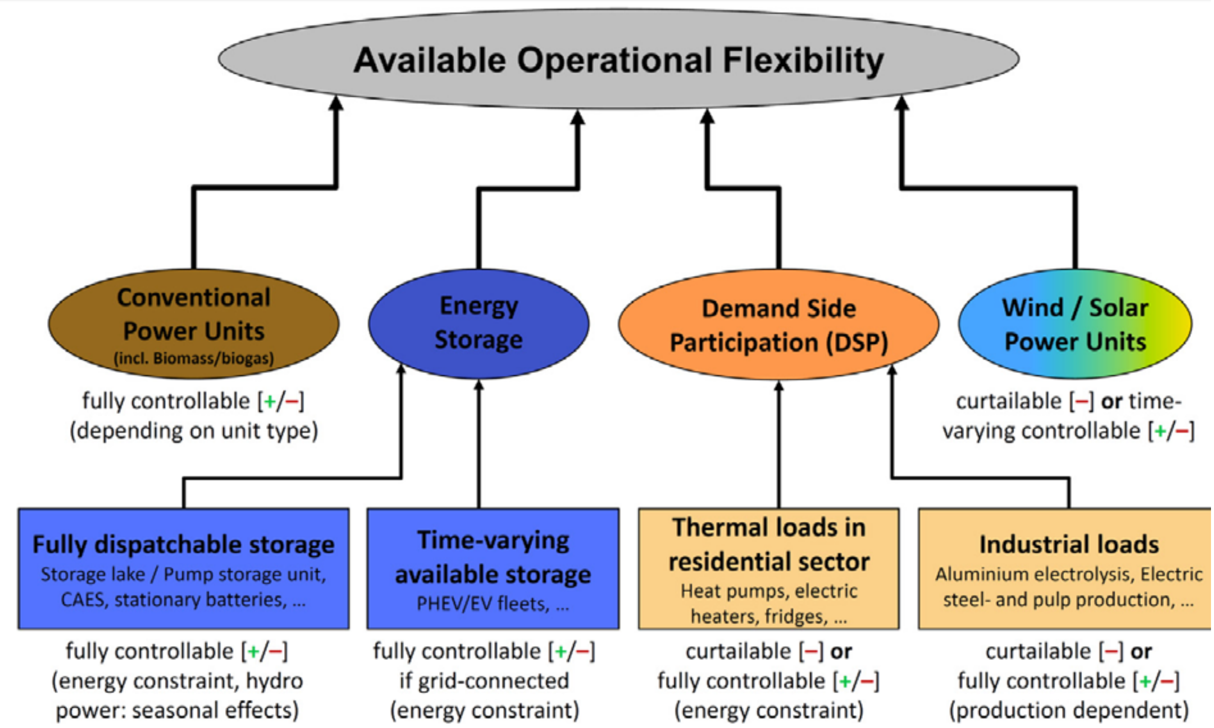

Figure 18: Flexibility options [32]

Particular attention should be paid to the fact that the flexibility is in a high correlation with security of supply. Namely, without enough flexibility the whole power system is jeopardized. Although transmission system operators are in charge for the stability and secure operation of the power system, distribution system operators (DSO) have a certain amount of responsibility as well – especially if distributed generation is considered. Distributed generation becomes an important issue when flexibility is considered from the DSO point of view. Due to the increased share of renewable energy sources, mostly photovoltaics, on a distribution level very often the DSOs have to deal with voltage control and congestion management. In that sense distributed consumers which would be able to take an active role in balancing the system are considered as a source of additional flexibility in the system. Namely, a conventional approach is focused on reinforcement of the infrastructure, while with the additional flexibility from the consumer's side intensive investments to the infrastructure would be avoided or at least decreased. However, for such a conceptual shift it is necessary to introduce certain business models, communication standards as well as to develop adequate technical infrastructure which will be able to support new circumstances within the power system. Of course, such an approach should be economically justified. Moreover, if consumers are considered as active participants in the power system, it can be concluded that this brings additional risk to the security of supply compared with the traditional approach, i.e. with traditional procurement of flexibility. Namely, the system operator depends on more participants in the system. Flexibility provided by the consumers imposes additional challenges to be further addressed because consumers must be incentivised and motivated to achieve not only the full benefits but also the full potential of flexibility provided by them.

Therefore, in the context of the Power-to-Heat/Cool concept it is necessary to observe the entire energy system in a holistic way. It is necessary to exploit synergies between different sectors within energy system such as electricity, heating, cooling etc. in order to fully leverage all available technical and economic benefits.

# III. TECHNO-ECONOMIC ASSESSMENT OF FLEXIBLE POWER-TO-HEAT / COOL OPTIONS

This chapter presents the current technical and economic parameters of different technologies relevant for PtH/C, as well as possible developments until 2030. Heat pumps, electric boilers, high temperature thermal storages and electric heating devices are selected as relevant technologies. A comparison of selected PtH devices with other heating technologies is undertaken. Finally, a comparative analysis of all applications for increasing flexibility in the European electricity system is presented.

## III.A. Power-to-Heat / Cool as a source of flexibility

In recent years the introduction of substantial amounts of intermittent renewable energy sources (RES) from weather-dependent sources in several European Member States has given rise to a number of concerns regarding the capability of the current and future electricity power systems to operate in a reliable and flexible service.

The increased contributions especially from wind and solar photovoltaic (PV) contributes positively to the decarbonisation of the power generation sector, but also may have the following effects to the power system:

- **Wholesale prices:** Intermittent RES impact the wholesale prices of electricity, as these plants, which have predominantly fixed costs shift the merit order curve; i.e. i) containing and even lowering the wholesale prices [24], and ii) substituting part of the generation of conventional thermal plants, which have higher marginal production costs. From the customer point of view this effect may be seen as beneficial, however from the utility perspective this reduced need for higher marginal cost generators to meet peak demand and may affect the revenue base of conventional thermal power generation. Analysis from [34] has shown that current market prices are already not sufficient to cover the fixed costs of all plants operating on the system, and this situation may become more critical in future, when more renewable energy will come online.
- **Flexibility:** Increasing amounts of power generation from weather-dependent renewable sources underpins a greater need for flexibility to maintain reliable power supply. Control power for the reliability of electricity supply is currently mainly provided by conventional power plants which must be rapidly ramped up and down over short periods of time in order to compensate for these fluctuations, but this ability may fall short in case of large intermittent RES contributions, causing curtailment.

In this context demand-side management (DSM) applications, which contribute to change the timing of end-use consumption from high-cost periods to low-cost periods and increase consumption during off-peak periods, may have an increasing role in future power systems, i) contributing to balancing the power system and making more efficient use of existing generating capacity, ii) producing environmental benefits contributing to reduce emissions, and iii) lowering customer electricity bills.

The potential role of several DSM applications have been assessed in a number of studies (e.g. [34]). These applications have been identified as promising systems to enhance demand-side flexibility and to interlink power and heat/cooling markets. The next sections provide a summary of these systems, an overview of the current development levels, the current policy framework and other elements.

### III.A.1. Relevant technologies and applications for flexible PtH/C

This section presents an overview of Power-to-Heat & Cooling options. These are represented by additional equipment, systems and controls enabling load shaping and providing linkages between the electricity and thermal markets.

A key component of PtH/C applications are thermal energy storage (TES) systems, which can store thermal energy by cooling, heating, melting, solidifying or vaporizing a material; and enables the mismatch between the heat production and demand. TES may be called i) sensible heat storage when the material temperature rises or falls; ii) latent heat storage when a phase change occurs; iii) thermochemical heat storage, when the process is based on a reversible chemical reaction. Different substances can be used, e.g. oils, molten salts, water, rock for sensible TES or ice, paraffins, salt hydrates for latent TES. They are chosen on the basis of storage period required, operative temperature, economic viability, etc. [35].

PtH/C systems make use of surplus electricity from renewables (i.e. low electricity prices) to generate heat or cold, and from a system point of view increasing the flexibility of electricity systems. This flexibility could be accomplished through i) distributed heat storage (i.e. hot water immersion heaters or storage-enabled heat pumps); ii) or at the larger scale by heat accumulators in district heating networks in industrial facilities. It is worth noting that a complete electrification of heat demand would require significant increases in capacity and flexibility (and thus reduced seasonal utilisation) of the power fleet. In contrast to pure electric heating and cooling systems, these PtH/C systems do not cause a permanent increase in electricity demand if operated based on economic principles.

The combined generation of heat and power in co-generation plants (CHP) can be exploited to link electricity and heat systems. Extraction-condensing co-generation technologies are able to regulate electricity and heat production; more importantly, where coupled to a district heating network, the thermal mass of the network or large hot water storage accumulators can be employed to increase the flexibility of the provision of heat and electricity. Such flexibility can, in turn, be used to provide balancing and other system services either locally to support integration of distributed energy resources, or to the larger system to balance intermittent renewable generation. Beyond co-generation and district heating, on-site heat storage can be enabled to respond to system signals [34].

In the literature, a number of system configurations are evaluated and estimated. This report identifies the following most promising PtH/C applications according to the current market outlook:

#### *III.A.1.i Distributed PtH/C applications for the residential and commercial sector*

- **TES and electric heaters**

- **Electric water heater:** These applications consist of grid-interactive heaters, where their target temperature can be set up or down in response to power availability (grid signal), the input wattage can be adjusted, providing the same comfort for the final user.
- **Storage heaters:** During off-peak periods these systems convert electric energy into heat which is stored in high mass units, or bricks, made of dense ceramic material. During the peak hours the power is shut off and an electric fan begins moving the heat from the brick to heat the home. The temperature is controlled by outside sensors that adjust the amount of power intake by how much will be needed to keep the room at the required comfort temperature [35]. An example of this application is shown in Figure 19.

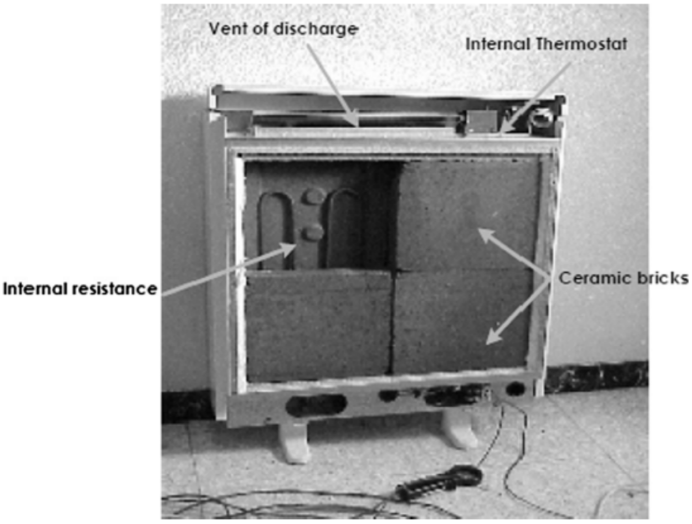

Figure 19: Example of storage heater [35]

- **Underfloor electric heating systems:** The floor is a large low temperature radiating surface. Some types of underfloor heating acts like a thermal storage heated by air, water or directly by electric resistances. Underfloor electric heating systems consist of shape-stabilized Phase-change material (PCM) plates which include polystyrene insulation, electric heaters, PCM, air layer and wood floor. Electric heaters heat and melt the PCM layer by using cheaper night time electricity and the system stores heat. During the day electric heaters are switched off and the PCM layer solidifies, discharging the heat stored [35]. An example of this application is shown in Figure 20.

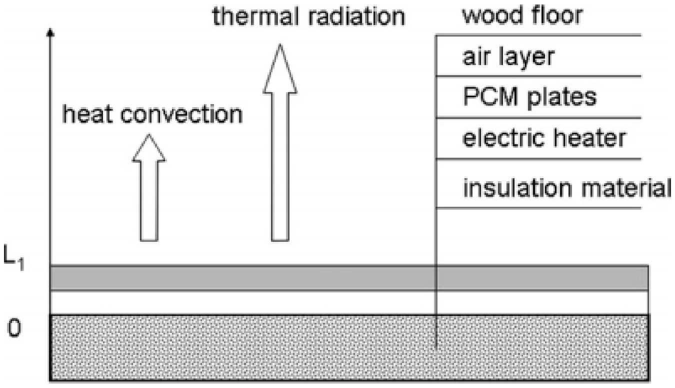

Figure 20: Example of underfloor electric heating system with shape-stabilized PCM plates [35]

- **TES and cooling:** Cold thermal energy storage is the most widespread on the market among the TES technologies used for load management. By adding a TES, the refrigeration system can be operated during the off-peak night time hours when the cooling demand is low and during the day time cooling can be supplied by recovering it from the cold storage, instead of using the chiller unit. In this way the refrigeration plant capacity can be reduced and a smaller unit plus storage meets peak capacity demands. Thus the smaller unit can be designed to operate at the optimum efficiency for the majority of its working time and generally smaller air handling units can be used because of the reduction in circulated air volume due to the larger air temperature difference. TES is particularly interesting for those buildings where cooling demands significantly contribute to the energy bill. Office buildings are ideal because of shorter occupancy periods and it is viable for those existing facilities undergoing an expansion and needing additional cooling capacity is a long term phased construction [35]. The application is commonly composed by a stratified water tank storage associated with a chiller.
- **TES and heat pumps:** Reversible heat pumps can be used both for PtH and PtC applications on buildings. They are efficient systems generally electrically driven using air, ground or water as a thermal source. Air source heat pumps have numerous advantages in many applications over other heating equipment with regard to energy efficiency, even if their performance decreases when the external air temperature decreases. This makes them more suitable in regions characterized by hot summers and winters with temperatures that do not fall below 0°C. Geothermal heat pumps can overcome these limitations, even if they are typically more expensive [35].
- **Hybrid Gas/Oil boilers with PtH systems:** Such installations consist of electric heating rods installed in the storage tank of decentralized conventional heating systems, such gas condensing boiler or oil-fired condensing boilers. Figure 21 provides a representation of this configuration.

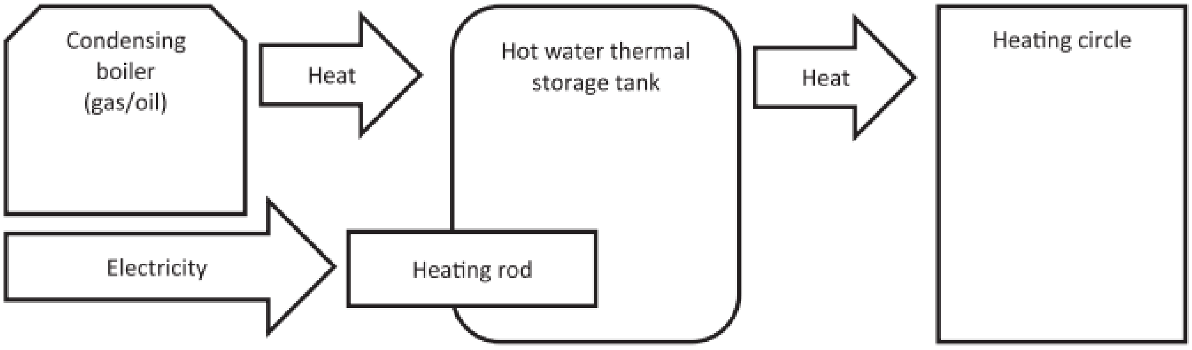

Figure 21: Decentralized PtH setup in the residential sector [23]

### *III.A.1.ii Large scale PtH/C applications*

- **PtH on an industrial scale:** Such installations consist of installing industrial electric boilers (e.g. high voltage electrode boilers) which are installed to complement existing heating generation systems, typically provided by gas-fired boilers or Combined-heat-and-power installations (gas engine, gas turbine, or combined cycle gas turbine). These are currently commercially available, the capacity ranges from 50 to70 MW and they have a steam output of up to 45 bar at 260°C. The technology is mature and can be operated flexibly, with ramp rates from zero to full output within 3 to 10 minutes timeframes [24].
- **PtH in District Heating Grids.** Such installations consist of adding a Power-to-Heat system (e.g. electric boiler) to the existing district heating CHP plants. The setup is similar to the application in an industrial level. However the business case and dimensioning should be based on district heating loads, generally used to feed residential and commercial heating requirements. According to Prognos [36], these systems should be sized between 30% and 50% of the maximum thermal load of the CHP-plant.

### *III.A.1.iii TES and CHP plants*

Coupling TES with combined heat and power plants (CHP) allows the decoupling electricity and thermal production. These applications can operate to follow the trend of electricity prices, generating electricity when power prices are high and storing heat when it is not needed. Using a thermal storage device prolongs the yearly operation time of the CHP plant, allows a continuous operation and causes a reduction in $CO_2$ emissions. Additionally, cogeneration using absorption chillers can be coupled with energy storage in order to maximize the utilization of co-generated chilled water for air-conditioning or achieve a better efficiency and cost effectiveness of the system.

## III.B. Power-to-Heat/Cool technologies

### III.B.1. Heat pumps

Heat pumps are devices that exchange energy between two heat reservoirs. In this regard, heat pumps utilize the energy potential of low temperature heat (heat reservoir at a lower temperature) and increase its temperature level by releasing heat energy at a higher temperature (heat reservoir of higher temperature) [37]. Such energy, at the higher temperature level, is more useful for further applications. In other words, heat pumps are devices that increase the temperature level of energy that is often widely available (heat of the air, surface water, soil, geothermal water, etc.) to a temperature level at which this heat energy is more useful. The aforementioned heat reservoirs of different temperature can be categorized as:

- Heat source: heat reservoir at a lower temperature level. From this heat reservoir the thermal energy is drained. Such heat reservoirs often represent widely available sources, such as environmental air, surface and ground water, soil, solar energy.
- Heat sink: heat reservoir at a higher temperature level. To this heat reservoir the thermal energy is delivered. Such heat reservoirs are, for example, air conditioned space heating, water heating or some form of medium heating.

Of course, the aforementioned temperature level increase of the available thermal energy is accompanied at a certain cost. The heat pumps require some mechanical work for their drive. The amount of mechanical work for the heat pump depends on the temperature level difference of required and available heat energy (the difference of temperature levels of the heat sink and heat source). With the increase of temperature difference, the required mechanical work to translate energy from lower to higher temperature levels also increases. This temperature difference is one of the key factors limiting the usefulness and hence the application of heat pumps [38].

Heat pumps can be classified according to various criteria. One of the main criteria is the required energy for heat pump operation and accordingly mechanical (i.e. compressor heat pumps) and sorption heat pumps can be distinguished. As part of this analysis, only mechanical heat pumps driven by electricity will be exclusively considered, since this report focuses on the conversion of electric power to heat.

When choosing the type and operation mode of heat pumps it is necessary to know the basic parameters that define the area of the heat pump application. The temperature level of the heat reservoir at a lower temperature (evaporation temperature), the temperature level of the heat reservoir at a high temperature (condensing temperature) and the available energy amount of heat sources can be stated as the basic parameters. In addition, it is necessary to select the refrigerant of heat pump, which can be divided into the following groups:

- Halogenated hydrocarbons;
- Pure hydrocarbons;
- Zeotropic mixture;
- Azeotropic mixture;
- Inorganic substances.

In April 2014, the F-Gas Regulation[10] was introduced and entered into force on January 1st, 2015. The aim of the Regulation is to reduce the use of fluorinated hydrocarbons as refrigerants and hence their impact on climate. One of the main objectives of the Regulation is to completely withdraw from the use the refrigerants whose GWP (Global Warming Potential) is higher than 2,500 by the year

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[10] 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

2020. This implicates that usage refrigerants which have atoms of fluorine or chlorine in molecular structure will be hinder, no matter to which group of refrigerants they belong to.

Heat pumps can also be used for cooling purposes, i.e. for the production of cooling energy. By doing so, the working principle and the components of the heat pump remain the same, a medium whose heat energy is drawn (conditioned air, cooling water) becomes a heat source, a medium where the heat is transferred (the environment, groundwater and surface water) takes on the role of heat sink.

When considering the use of heat pumps in district heating systems, it is necessary to provide a large temperature increase between the heat source and heat sink. In such cases, special performance heat pumps are used, such as cascade or multistage heat pumps (usually two-stage heat pumps). By using such types of heat pumps, various positive effects on the technical performance of heat pumps are achieved. The cascade type of heat pump is a system that is essentially composed of two heat pumps each of which each uses a different refrigerant. Multi-type heat pumps use the same refrigerant, but have multiple compression [39], [40].

In order to evaluate the operation of heat pumps, certain indicators are defined. The basic value for assessing the efficiency of the heat pump in heating mode is the so-called COP factor (Coefficient of Performance). The COP factor is defined as the ratio of produced useful heat and electricity needed for the power of the heat pump.

When considering the work of the heat pump in cooling mode, i.e. when the heat pump produces cooling energy, the basic value for assessing the efficiency of the heat pump is so-called EER cooling factor (Energy Efficiency Ratio). EER factor is defined as the ratio of the exhausted heat energy (i.e. cooling capacity) and the electricity needed for the power of heat pump.

COP and EER factors are linked with the following simple equation:

$$\mathrm{EER} = \mathrm{COP} - 1$$

Below, the graphical representations of the COP and EER factors for two-stage heat pump with refrigerant R134a [41] are given.

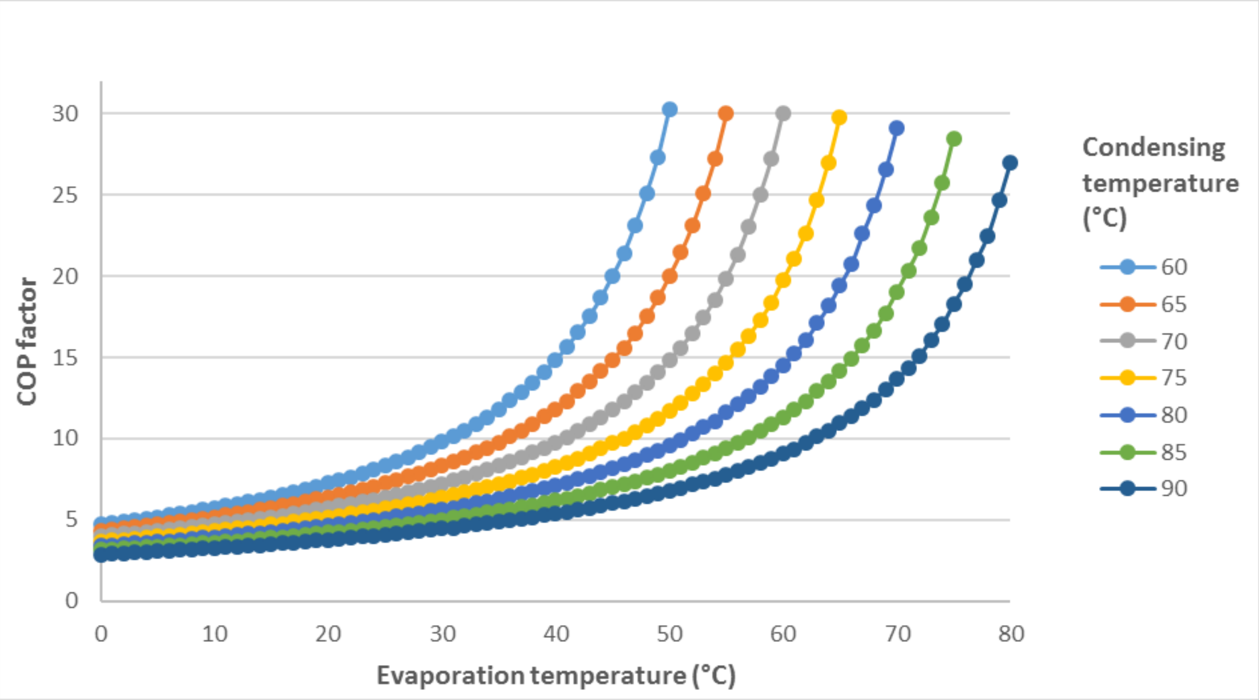

Figure 22: COP factor for two-stage heat pump [41]

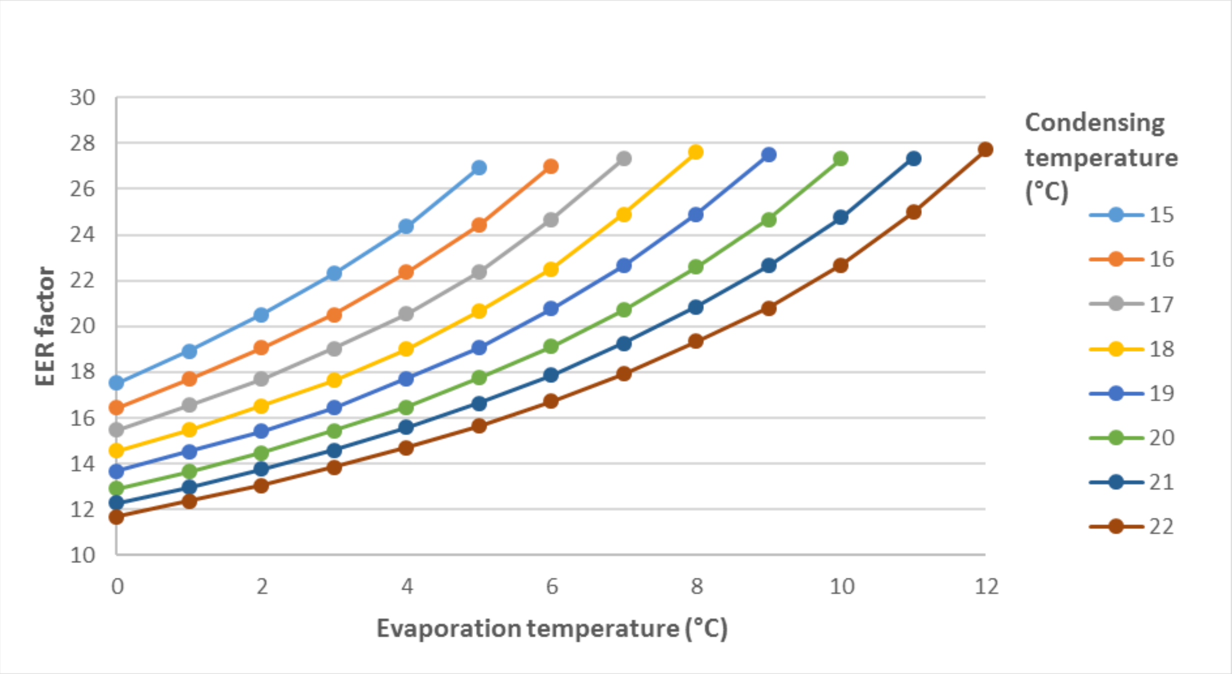

Figure 23: EER factor for two-stage heat pump [41]

Heat pumps in the context of PtH/C can be used not only to utilise great amount of excess renewable electricity, but also as a provider of ancillary services, i.e. to provide control power. When considering the control power, heat pumps can be mainly considered as the provider of negative secondary control power due to the response time of the heat pump. Moreover, heat pumps can achieve relatively high ramp rates which make them suitable to provide balancing energy.

Heat pumps in the large-scale application very often are realized as more units of a smaller capacity (2 to 20 $MW_{th}$) which can be assessed as technically desirable solution due to the fact that reliability is increased while downtime is decreased. Moreover, such solutions are more flexible in operation and achieve better efficiencies. Investment cost of large-scale heat pumps is approximately 450 to 850 $EUR/kW_{th}$.

### III.B.2. Electric boilers

An electric boiler is used for producing heat directly from electricity. Boilers can provide heat for water heating, space heating and process heating (in industrial technologies).

Two types of installations are available: heating elements using electrical resistance (same principle as a hot water heaters used in households) and heating elements using electrode boilers (the current from the three phase electrodes flows directly through the water, which is heated in the process).

Except by the type of installation, electric boilers can be distinguished according to their capacity and temperature application.

Typically, electrical resistance is used for smaller applications up to 1-2 MW. These electric boilers are connected at 400 V. Electrode systems are used for larger applications (larger than a few MWs up to 25-30 MW). Larger electrode boilers (larger than a few MWs) are connected at 10 kV. The energy efficiency of both types of electric boilers is 99%, while the temperature range is flexible. It is possible to use different types of electric boilers in applications in residential areas, district heating and industries, also it is possible to install applications in industries that produce steam [42].

The temperature application of electric boiler is particularly important in industry, where different technologies utilise heat at different temperatures:

- high temperature applications (above 1000 °C) – used for process heating e.g. within the production of iron and steel and the production of bricks and cement;
- medium temperature applications (120 - 1000 °C) – used in the production of plastic materials, plasterboards, bitumen, asphalt and in drying technologies;
- low temperature applications (below 120 °C) – used in industries such as dairy, breweries, chemicals, food industry, textile industry, mineral oil industry etc.

Electric boilers have a simple design, they are very dependable, easy to maintain and to operate – their output can be controlled to a large extent. The electric system is suitable for smaller installations with lower voltages and power capacities while the electrode boiler system is suitable for larger installations with higher voltages and power capacities due to lower installation expenses. The major disadvantages of district heating systems coupled with large scale electric boilers (capacities of up to 25-30 MW) are distribution losses, high dependence on electricity prices and possible congestions in the distribution grid. Electrode boilers can be controlled between 10-20% and 100% of the nominal load.

No significant variation in performance or investment costs is expected for boilers in the near future. Until 2030 efficiency of electric boilers is expected to remain 99%. According to the study [43] investment cost of electric boilers amounts to 230 EUR/kW[11], but investment costs are very dependent on the size of the boiler. Energinet.dk study [44] provides estimations for investment cost of electricity boilers for different capacity classes, and according to which investment cost is 50-90 EUR/kW for boilers with capacity 10-20 MW, while investment cost for boilers with 1-3 MW capacity amounts to 130-160 EUR/kW. Thus, it can be concluded that investment costs for electric boilers vary in a wide range depending on the location, nominal capacity, type of installation, temperature application, etc.

Operation and maintenance (O&M) costs are between 1 and 2% of the investment costs, while operating costs of boilers depend significantly on electricity prices. Larger electrode boilers with a capacity of up to 25-30 MW used in district heating systems usually have a lifetime of 20 years [43].

### III.B.3. Electric heating devices

Decentralised electrical heating systems usually consist of radiators installed in each room. Rooms can also be equipped with electric floor heating systems, e.g. in bathrooms. The heat is generated by electric resistances. Older electric radiators have internal thermostats, which only regulate the room temperature. Later electric heaters are often equipped with more intelligent technology allowing the programming of temperature schedules for each individual room, the external control of the heating system or even remote internet control. Radiators can be constructed as storage heaters. Storage heaters can still deliver heat after the electricity is turned off. These systems can generate heat using low electricity prices in periods of high electricity generation and low consumption, and thereby help to balance the electricity grid.

The use of direct electric heating is highly dependent on the energy sources and energy policy of countries. For example, storage heaters were, and still are used in countries with a high share of nuclear power in electricity production as surplus electricity generated during the night can be utilised by storing the heat. Direct electric heating is also widespread in countries which have significant electricity generation from hydro power and in countries where there are only a few cold days during winter. In such countries the installation of a water-based heating system with boilers is too expensive and the degree of utilisation would be very low. In these countries the installation of decentralised and cheap electric heating systems can be the most cost-effective heating technology.

Electric heating systems in buildings usually have a capacity of 5 to 400 $\text{kW}_{\text{th}}$. One major advantage of electric heating systems is their flexibility (from 0 to 100% and vice versa with high ramp rate and neglectable response time) and there are no distribution losses as there is no heat distribution in the buildings. In the following, small scale electric boilers mainly used in households are characterised in terms of their thermal efficiency, technical lifetime, specific investment and operation and maintenance (O&M) costs. In Table 6 the thermal efficiency of the boilers is listed together with specific investment costs of electric heating systems in buildings (according to [43] this investment cost comprises the whole system of heating in building including heater, installation and control unit).

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[11] Investment cost is in euros, 2014 price-level and harmonized to the EU28 Price Level Index (PLI EU28 = 100).

Table 6: Thermal efficiency of small scale electric boilers and specific investment costs of electric heating systems in buildings (based on [43])

| | < 25 $kW_{th}$ | 25 - 100 $kW_{th}$ | 101 - 250 $kW_{th}$ | 251 - 400 $kW_{th}$ |
|---|---|---|---|---|
| **Thermal efficiency (%)** | 96 - 100 | 96 | 100 | 95 - 100 |
| **Specific investment costs ($EUR/kW_{th}$)** | 243 - 800; average 480 | 240 - 789; average 474 | 228 - 750; average 450 | 202 - 665; average 399 |

The thermal efficiency of small scale electric boilers is presented for different capacity classes, but mainly ranges from 95 to 100%. Specific investment costs vary around 450 $EUR/kW_{th}$ depending on the capacity, as presented in the table. O&M costs are between 0 and 0.1% of the investment costs, since there are no engines and no fuel is burned. In addition, the electrical elements in the heating systems are long-lasting. The technical lifetime of electric heating systems in buildings is 30 years. As small scale electric boilers are an established and widespread technology no major efficiency increases are expected in the future, also it is not expected that the investment and O&M costs will be reduced until 2030. The only major developments expected are those providing the ability to interact with the electricity grid and the ability to balance the grid (integration into smart grids) [43].

Decentralised electricity systems for cooling are based on compression cooling (room air conditioning). In order to produce cold as a useful energy service, the refrigerant fluid is compressed by an electrically powered compressor to raise pressure and temperature. Afterwards it is cooled down in a condenser where it turns back to a fluid by exchanging the heat with a coolant. Refrigerant passes through an expansion valve where it expands to lower pressure and temperature and is able to cool down the coolant, which is on a higher temperature level. Every compression cooling system has four basic elements which are run through by the refrigerant continuously – evaporator, compressor, condenser and throttle. The efficiency of cooling processes is usually given as the Energy Efficiency Ratio (EER), which is the equivalent of the Coefficient of Performance (COP) in heat supply systems (heat pumps). Residential air conditioners are constrained by a capacity limitation of 12 kW, while EER ranges between 1.9-4.3 [43].

## III.C. High Temperature Thermal Storages

High temperature thermal storages can be divided according to the storage material. Thus, it is possible to distinguish thermal storages of sensible heat and thermal storages of latent heat. More detailed representation of further subdivision of storage materials is given in the Figure 24. When analysing high temperature thermal storages, into consideration can be taken molten salts in the case of sensible heat storage systems, while in the case of latent heat storage systems as the most convenient storage material can be considered solid-liquid phase change material.

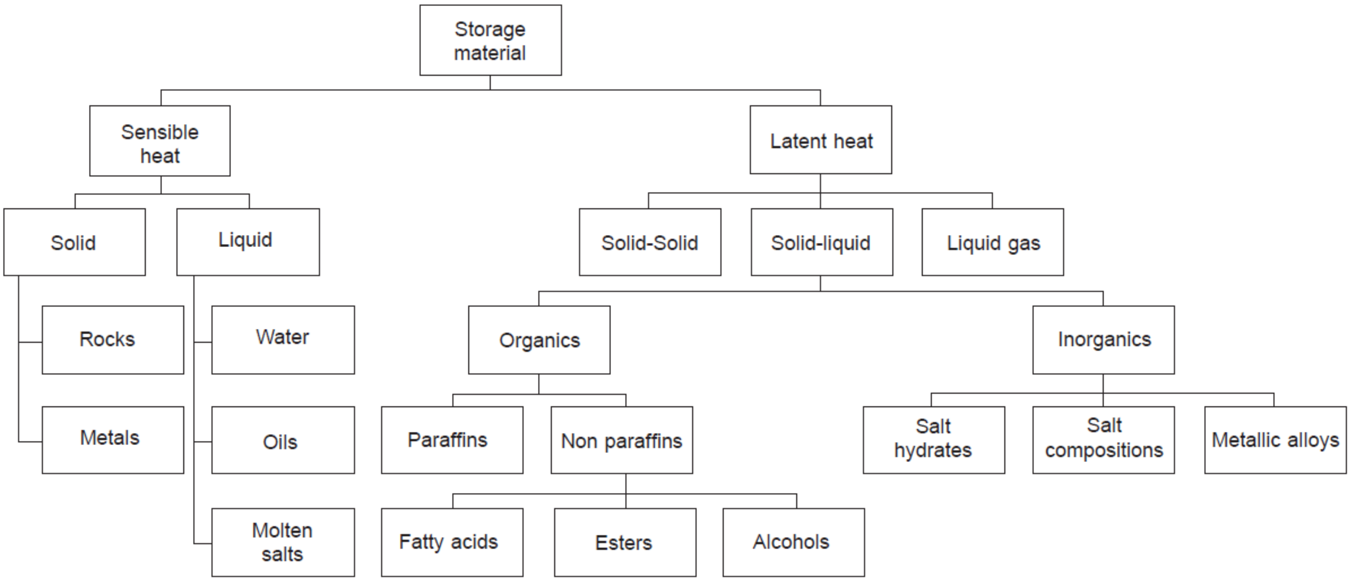

Figure 24: Classification of thermal storage materials [45]

High temperature thermal storages can be used for the process industry in the context of PtH/C because significant amount of excess renewable electricity can be utilised. Moreover, such thermal storages have important roles in the case of solar thermal power plants (e.g. CSP) which enable more flexible electricity generation from the mentioned power plants. However, such applications will not be further addressed within this report.

The observed thermal storages can be coupled with different heat generation technologies but as the most logical, within the PtH/C context, are electric boilers which can utilise electricity in order to produce thermal energy of a high temperature necessary for industrial purposes. More details regarding the electric boilers are given in the section dedicated to that technology.

The most significant operational differences between latent and sensible heat storages are the temperatures of operation and energy density. Although thermal storages of sensible heat are more proven, i.e. mature technology compared to the storages of latent heat, the latter are characterised with a higher energy density and a very narrow operational temperature range (at almost constant value around the melting temperature) [46], as can be seen in the Figure 25.

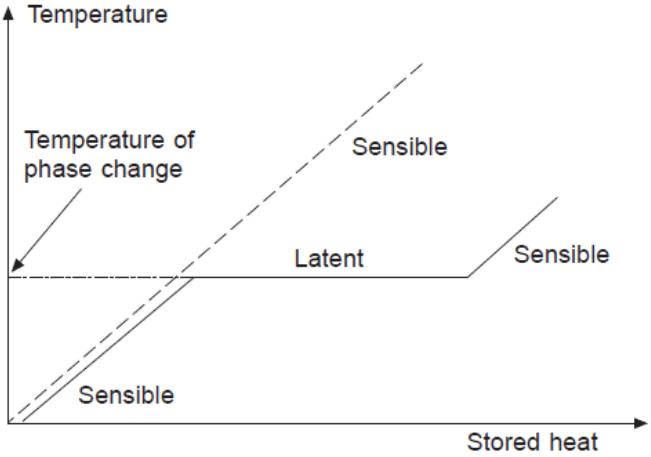

Figure 25: Schematic range of operational temperatures of thermal storages of latent heat (solid line) and thermal storages of sensible heat (dashed line) [45]

The operational temperatures of thermal storages of latent heat are in the range of 300-550 °C, depending on the type of phase change material. In the case of the thermal storage of sensible heat that uses molten salts, operational temperature is from 120 to 530 °C. However, here it is necessary to emphasize that in the cases of molten salts operational temperatures are not constant during charging and discharging of the heat storage, but vary from approx. 10 to 400 °C, depending on the type of molten salt [45].

## III.D. Comparison of the selected technologies

In order to compare selected technologies, the average values of technology efficiency, investment costs, O&M costs as well as other economic assumptions are taken into account. The values were determined based on the data provided in the previous chapters.

Table 7 provides an overview of the performance (efficiency) and investment costs of these technologies. In terms of efficiency, heat pumps are the most efficient technology. However, utilization of heat pumps is determined by abundance of a suitable heat source, thus very often heat pumps cannot be used as the main heat source. The Electric boilers are the economically most acceptable technology in terms of investment cost.

Table 7: Technology performance and investment costs overview

| Technology | Total efficiency[12] | Nominal investment (EUR / kW) |
|---|---|---|
| **Electric boilers** | 0.99 | 70 |
| **Gas boiler** | 0.90 | 180 |
| **Heat pumps, large, COP 2** | 2 | 600 |
| **Heat pumps, large, COP 3.5** | 3.5 | 600 |

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[12] Although it is not completely correct, for the purpose of this report total efficiency equals the coefficient of performance (COP) when heat pumps are considered.

For profitability comparison of each technology, the price of generated heat was determined not only based on the operational, but also on the investment expenditures. The operational expenditures comprise the variable cost for operation and maintenance depending on the number of working hours and the fixed costs for operation and maintenance. The investment costs were discounted for the lifetime period (25 years) according to the chosen discount rate (set to 8%). Apart from the mentioned costs, cost of the generated heat depends on the costs for the fuel (electricity or gas) as well. For the purpose of this report the electricity and gas price was based on the average prices across EU 28 in 2015 [47] for industrial consumers. The electricity and gas price was set to the value of 119 EUR/MWh and 34 EUR/MWh, respectively. In the Figure 26, impact of the number of operational days on the price of generated heat of certain power-to-heat technology can be seen. Moreover, price of generated heat from CCGT and gas boiler was also given in order to give an insight in profitability of PtH technologies compared to the conventional ones.

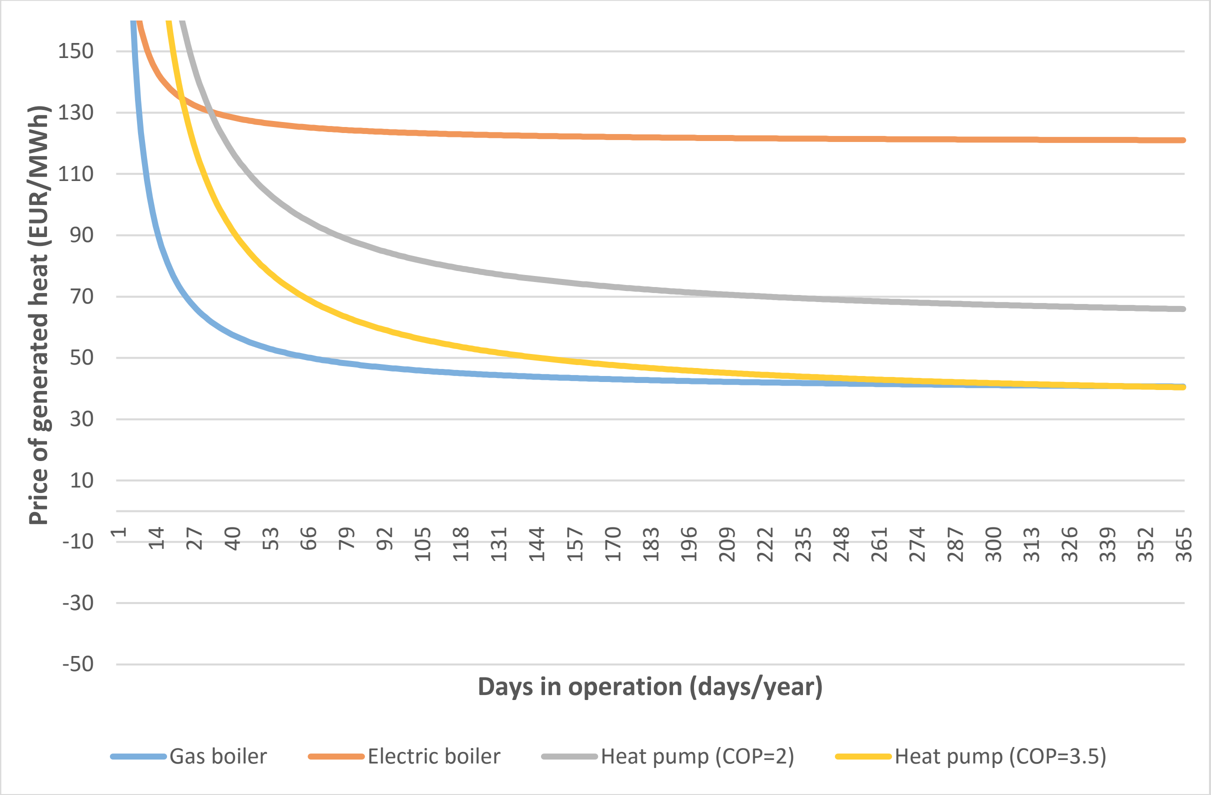

Figure 26: Price of generated heat overview

Heat pumps achieve the lowest price of generated heat if they operate more than 80 days yearly, while electric boilers are the most suitable technology in the case of a lower number of operating days due to the lower investment cost. Compared to the selected PtH technologies, gas boilers are also competitive and represents an acceptable option in terms of generation cost.

## III.E. Comparative analysis of applications for increasing flexibility in the European electricity system

As mentioned earlier, the stability of the power system must be assured in any case. There are different ways and all of them can be categorised as some kind of flexibility provided to the power system. Conventional sources of flexibility are related to flexible generation assets such as gas turbines or hydro power plants. Apart from gas turbines and power plants fuelled by natural gas, power plants fuelled by coal or fuel oil can provide a certain amount of flexibility as well. However, the most important features of any generation asset, in the light of flexibility procurement, are its dynamic performances such as ramp rate, response time, duration of cold/warm start (in the case of thermal power plants), minimal load, etc.

Minimal possible load is a very important feature of any generation asset. During operation periods with decreased load several negative impacts occur, such as poor power control, poor environmental control performances, limitations with air-flow control, flame stability etc. It is necessary to emphasize that efficiency of each technology is highly load dependant. Namely, when generation is lower than nominal, efficiencies are reduced significantly – compared to the efficiencies at nominal power output. However, diesel engines achieve the best performances at part load – changes in efficiency are insignificant [48].

In the context of dispatch, important feature of a generation asset is the duration of the start, i.e. number of hours necessary for power plant to be ready for synchronisation with the grid. Duration of the start-up time is dependent on the time thermal power plant was offline. Thus, for thermal power plants three different types of starts can be distinguished, shown in Table 8.

Table 8: Definition of start types for thermal power plants

| Start type | Time since shutdown | Metal temperature |
|---|---|---|
| **Hot Start** | **< 8 h** | **> 400°C** |
| **Warm Start** | **< 48 h** | **> 200°C** |
| **Cold Start** | **> 48 h** | **< 200°C** |

It can be concluded that the longer the thermal power plant is offline, the longer period is needed to be ready again for synchronisation with the grid, with no damage imposed.

Regarding ramp rates, in the literature review it is possible to find different values for different technologies. Table 9 gives a comprehensive overview of the most important dynamic performance indicators of thermal power plants fuelled by hard coal and lignite, together with combined cycle gas turbines (CCGT) and gas turbines (GT).

Table 9: Dynamic performance of conventional generation assets [49]

| Power plant type | | Hard coal | Lignite | CCGT | GT |
|---|---|---|---|---|---|
| Minimum load | ($\%P_n$) | 20–40 | 40–60 | 30–50 | 20–50 |
| Ramp rate | ($\%P_n/min$) | 1.5–6 | 1–4 | 2–8 | 8–15 |
| In load range | ($\%P_n$) | 40–90 | 50–90 | 40–90 | 40–90 |
| Start-up time | (h) | | | | |
| Hot | (<8 h) | 1–3 | 2–4 | 0.5–1.5 | <0.1 |
| Warm | (8–48 h) | 3–6 | 4–7 | 1–2 | <0.1 |
| Cold | (>48 h) | 4–10 | 6–10 | 2–4 | <0.1 |

The exploitation of the flexibility in conventional power plants does not only depend on retrofits or new investments. Due to historically evolved inflexible power plant operation, there is also room for improvements in flexible operation.

Apart from the aforementioned technologies (besides pumped hydro PP) which provide flexibility to the power system there are some additional technologies which can be deployed as flexibility sources in the sense of both positive and negative balancing energy. In other words, these technologies are not only generation assets, but also assets which can be utilised to consume excess electric energy. Some of them are in the mature phase of development, while some of them still are not commercially justified for wider deployment. In that sense the following technologies can be stated as other flexibility options: electric batteries, Compressed Air Energy Storage (CAES), flywheels, Superconducting Magnetic Energy Storage (SMES), supercapacitors, fuel cells.

Electric batteries can be divided into the so-called classic batteries which can be recharged, NaS batteries and Flow batteries. The most common type of classic batteries is LI-ion battery which is often deployed in mobile phones and laptops, but they can be deployed in the systems of greater capacities (50 kWh) as well. NaS batteries are mainly used for peak load covering and the most typical power capacity of such batteries is 360 – 430 kWh with a power output of 50 kW. Flow batteries are used to store greater amounts of energy [50].

Compressed air energy storage operates in the way that excess energy is used for compressing air to high pressures and storing it in air storages, such as different geological formation (e.g. abandoned mines). During the compression the air is heat up. To avoid thermal stress and the resulting breakdown of the geological storage formation the compressed air needs to be cooled down before the injection into the geological formation. In the reverse process, compressed air is mixed with fuel in the gas turbine when generating electricity. Thus, the necessary work for air compression is reduced comparing to the conventional process in gas turbine.

Supercapacitors have the same operation principle as conventional capacitors, but the electrode's surfaces are enlarged by usage of porous materials, such as nanoparticles of graphite. They can be deployed in the systems with capacity below 250 kW.

Flywheels store energy in the form of kinetic energy of rotation. The amount of stored energy is proportional to the inertia moment of flywheel's rotor. They have an extremely fast response time, less than 4 ms, while power output is between 100 kW and 1.5 MW [50].

Superconducting Magnetic Energy Storage uses a magnetic field of direct current to store energy, i.e. energy is stored within superconducting electromagnetic coil. The efficiency of such system is extremely high 90-99% and response time is very short [50].

Fuel cells use hydrogen to produce electricity as well as water and heat as by-products. Hydrogen is the form of energy which is obtained in the reverse electrochemical process where excess electricity was used to produce hydrogen and oxygen. However, fuel cells, i.e. hydrogen technology is still not sufficiently developed for providing flexibility to the power system [51].

Table 10 gives a comprehensive overview of the main characteristics of the aforementioned technologies.

Table 10: Overview of the main characteristics of flexibility options (based on [50] and [51])

| Technology | Power | Energy | Discharging period | Technology development | Lifetime | Investment cost (€/kW) | Efficiency |
|---|---|---|---|---|---|---|---|
| **Classic batteries** | < 500 kW | < 100 MWh | 1 - 8h | Mature | 4 - 8 y | 1700 - 2500 | 90 |
| **NaS batteries** | 1 MW | 1 MWh | 1 h | Commercially available | 15 y | 1850 – 2150 | 80 - 85 |
| **Flow batteries** | 10 kW – 10 MW | 1 - 100 MWh | 10 h | Demonstration | 10 - 20 y | 5000 – 8000 | 75 - 80 |
| **CAES** | 25 - 3000 MW | 200 MWh - 10 GWh | 1 -20 h | Demonstration | 35 y | 600 – 750 | 54 - 88 |
| **Supercapacitors** | < 250 kW | 10 kWh | < 1 min | Developed | > 500000 cycles | 1500 – 2500 | 90 |
| **Flywheels** | 100 kW - 1.5 MW | 100 kWh - 100 MWh | < 5 min | Mature | 20 y | 3700 – 4300 | 90 |
| **SMES** | 10 kW – 10 MW | 10 kWh – 1 MWh | 1 - 30 min | Commercially not available | Few hundreds cycles | 3000 – 5000 | 90 |
| **Fuel cells /hydrogen** | 1 kW – 10 MW | Unlimited | > 5 h | Developing | - | 2000 - 3000 | 32 - 55 |

All technologies stated in the table have response times on the level of a few seconds, except of CAES and fuel cells. Therefore, all these technologies can be deployed as flexibility options and provide additional support to the conventional flexibility sources when stabilisation of the power system and security of supply are in question.

Figure 27 compares different technologies in the sense of investment cost per unit of power versus per unit of energy. However, it is necessary to draw attention to the fact that economy should not be the only driving force when selecting certain technology as a flexibility option, but also social, environmental and technical requirements must be satisfied.

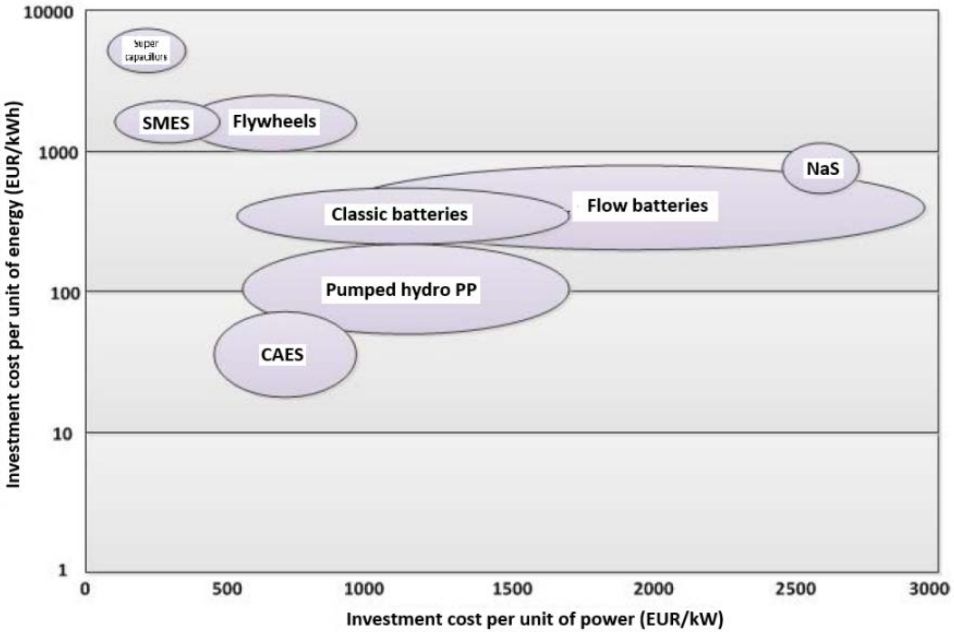

Figure 27: Investment cost of different flexibility technologies (based on [50])

Another set of options for providing additional flexibility to the electricity system are demand side options. Such options traditionally had a limited role for system flexibility. However their large technical potential and the increased flexibility needs may help to overtake the current market barrier. These options come from demand management in energy intensive industries, services and smart applications; the electrification of key end use sectors such as space and water heating, and electro-mobility and the conversion of electricity to liquid or gaseous fuels [52].

Demand management (DM) in industrial installations is the most mature option. It is shaped by the characteristics of specific industrial processes, and can vary among industries. The costs of providing flexibility are generally modest if the primary process is not disrupted. Costs generally relate to change of shifts in personnel, installation of communication and control equipment, and additional on-site storage of intermediary products. Costs associated with reduced production can be high and are usually avoided. The potential of the option is high and is easy to realise, however its realisation will depend on sufficient incentives.

Demand management in services and households can especially be applied in cross-section processes such as providing heating and cooling. This includes different levels of electricity demand, e.g. selective timing of the cooling of cold storage warehouses as well as automatic adjustments in the demand of refrigerators. Other potential demand management technologies include air conditioning, compressing air for mechanical use or even rescheduling of washing processes in households. Some municipal water systems can provide the direct equivalent to pumped storage hydro by timing the reservoir refill to the needs of the power grid. Pooling of different demand potentials makes use of the inherent reservoir storage. The potentials of these applications are very high, but enabling the infrastructure to selectively control devices can present significant challenges.

Additionally, electric vehicles (EVs) can make use of electricity stored in electric vehicles´ batteries, selectively charged by the grid when the vehicle is parked at a charging point. The characteristics of transportation demand allow fleets of EVs to be used as a flexibility option for the power system in two key operational modes: i) Grid-to-Vehicle (G2V), where fleets of EVs are operated as a demand side management option, enabling a shifting of the charging times; or ii) Vehicle-to-Grid (V2G) where in addition to charging, the batteries of EVs could be discharged and feed power to the grid. Due to their primary use as means of transportation, the provision of flexibility from EVs is subject to many constraints and is inherently uncertain. One key advantage is that EVs form a parallel development and as such their investment costs are driven by the transport sector.

Alternatively, "Power-to-X" options may have a potential in future energy markets. These can be distinguished between Power-to-Gas (production of gaseous fuels as hydrogen or synthetic natural gas), Power-to-Liquids (production of liquid fuels, e.g. methanol, synthetic diesel), and Power-to-Heat/Cool.

Power-to-Gas (PtG) and Power-to-Liquids (PtL) are options that can be considered as a solution to convert power into fuels for energy markets. These systems employ electrolysis, electro-reduction or co-electrolysis to contribute, aside system flexibility, on greening the transport sector or other end-use sectors (e.g. injecting green gas to the natural gas networks) [52]. However, these technologies had generally a limited success given their high costs.

Within this branch Power-to-Heat/Cool seems quite promising. The conversion of electricity to heat has a large number of uses and applications in industrial, commercial and residential sectors and generally low costs. PtH/C applications electricity can be used to replace other fuels such as gas or oil for heating and cooling purposes, and at the same time provide load demand management. Small scale applications (e.g. residential applications) make use of direct resistance heating or of electric heat pumps (HP). Flexibility is provided by selectively activating the heaters and storing the generated heat for later use. Thermal energy can be relatively efficiently stored in a number of ways, most commonly including insulated ceramic brick containers and hot water tanks. Heat is released as needed by the end user from storage. Resistance heating is generally cheaper, however electric heat pump technology offers a more efficient technology conversion of electricity to heat; and may also be employed for air conditioning and refrigerating applications (PtC). Large scale applications make use of large electric boilers or large heat pumps to complement existing heating generation systems. These are generally attached to large storage systems and/or district heating networks. District heating applications temperatures generally range below 100 °C, industrial applications may range from below 100 to over 1,000 °C depending on the application.

Figure 28, taken from [52], provides an overview of "Power-to-X" applications:

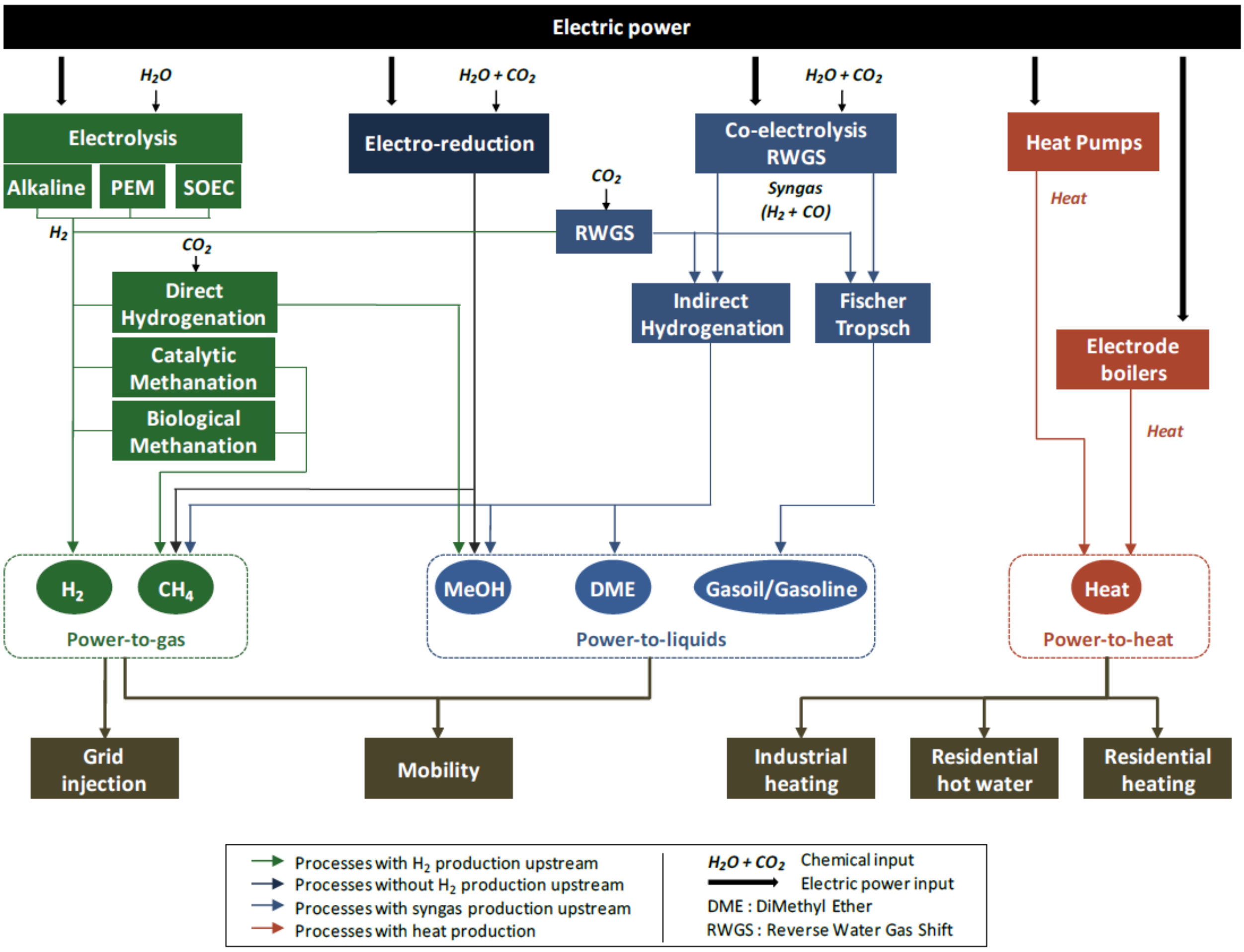

Figure 28: Overview of "Power-to-X" route options [52]

The following Table 11 gives an indicative overview of the main techno-economic characteristics of the aforementioned technologies. It is worth noting that compared with other *advanced* flexibility options such PtH/C, PtG, PtL and electric vehicles have a "dual" function. They provide energy services, such as heat to households in the case of PtH applications, and they enable flexibility in the electricity system. These should be taken into account in the comparison of alternative business cases.

Table 11: Overview of the main demand side flexibility options, including PtH/C (own elaboration based on [53], [52], [44], [24], [23] and [54])

| Technology | Power | Energy | Discharging period | Technology development | Lifetime | Investment cost | Efficiency |
|---|---|---|---|---|---|---|---|
| **DM in industry** | N/A | N/A | 1 - 24 h | High | N/A | N/A (Low) | 95% - 100% |
| **DM in households and services** | N/A | N/A | 1 - 24 h | Low | N/A | 300 – 370 €/installation (meter, gateway and installation) | 95% - 100% |
| **EVs** | ~ 6.5 kW/vehicle | ~ 29 kWh/vehicle | Hours | High (battery)<br>Low (for flexibility) | 5 - 15 y | 15000 - 30000 € (vehicle) | 93% |
| **PtG** | 1 - 10 MW | 4 - 40 GWh | N/A | Low | 20 – 25 y | 1000 - 6000 €/kW$_e$ | 66% - 69% (electrolyser)<br>79.4% (methanation) |
| **PtH/C small boiler** | 3 - 9 kW | ~ 2 hrs load (100 - 500 l) | up to 24 h | High | 15 - 20 y | 196 - 248 €/kW$_e$ (boiler) | >99% |
| **PtH/C small HP** | 5 - 25 kW | ~ 2 hrs load (100 - 500 l) | up to 24 h | High | 15 - 20 y | 530 – 2560 €/kW$_e$ (HP) | 3 - 5.5 (COP) |
| **PtH/C large scale IND** | 1 - 90 MW | 5000 - 10000 m$^3$ | hours to year | High | 20 | 60 - 190 €/kW$_e$ | >99% (boiler)<br>50 - 90% (storage) |
| **PtH/C large boiler DH** | 1 - 90 MW | 5000 - 50000 m$^3$ | hours to year | High | 20 | 88 - 180 €/kW$_e$ | >99% (boiler)<br>50 - 90% (storage) |
| **PtH/C large HP DH** | 0.5 - 15 MW | 5000 - 50000 m$^3$ | hours to year | High | 20 | 527 (ASHP)- 1321 (GSHP) €/kW$_e$ | 1.7 - 3.8 (COP)<br>50 - 90% (storage) |

Flexibility applications cover a wide variety of technologies and options. They can be classified as “supply” measures, “storage” options, and “demand response” applications. A direct comparison is not always possible given the different nature of these mechanisms and the different energy sectors included. Hence a number of qualitative criteria is identified in order to compare different flexibility options with PtH/C technologies and to assess strength and weaknesses of each option. The list of identified criteria together with its description can be found here below.

- **Level of maturity**

  Level of maturity provides information whether certain technology is developed and commercially proven. Most of the PtH/C technologies can be declared as mature technologies, in the way that they are ready to be deployed as the means of flexibility. Of course, conventional sources of flexibility have a high level of maturity as well, while some storage options together with DM side options are still developing.

- **Response timeframe**

  Perhaps the most important indicator among others is flexibility timeframe. Namely, as this policy report focuses on power system flexibility, a very important feature of a certain technology is its response time regarding the disturbance in the power system. Due to the fact that all stated technologies are considered to participate in power system stabilisation they all can provide a certain amount of flexibility in the short to medium term. This indicator does not reflect the amount of energy or power that a certain source of flexibility is capable of providing, but the time needed to respond on disturbance.

- **Political commitment**

  The main idea of such an indicator is to keep track of possible plans / incentives / preferences, or of any "evident" effort aimed at boosting the penetration of the specific technology. Making use of the findings of the Insight_E report “Exploring the strengths and weaknesses of European innovation capacity within the Strategic Energy Technologies (SET) Plan” [55], the expenditures in R&D “by type of technology” are assumed to be the proxy for the level of political commitment. In particular, R&D expenditures in electrical and electrochemical technologies, as well as in small size heating/cooling options, indicates that the focus is on these technologies at EU level.

- **Difficulty of implementation**

  This indicator aims to report the easiness / complexity of implementation (evaluated in qualitative terms) of the technologies. An overview of the international (ISO, IEC) and European (CEN) standardisation bodies would provide a robust representation of the actual difficulty of implementation (when a “standard” does not exist or is not perfectly evident, a bad qualitative performance can be attributed to the technology), but such activity is very time consuming and would deserve a dedicated report. A more simplified approach is to look at some available figures (in particular, number of patents and publications) to estimate the strengths and weaknesses of the EU with respect to those technologies. The difficulty of implementation is supposed to be high when the technical “knowledge” of the EU on the technology is low.

- **Closeness to demand consumers**

  This is a simple criterion, which aims to highlight the closeness of the technologies to the demand side (final consumers). The key underpinned assumption is that the “benefits” of penetration of some technologies are “directly perceived” by the final consumers (savings, end-use flexibility), while others are more oriented to “system” optimisation, storage and management, and supply.

Table 12 depicts a comprehensive overview of selected criteria for various flexibility options in the contemporary energy system, organized in three sections (supply, storage and demand response).

Table 12: Comparative assessment of flexibility options characteristics (own assessments of EIHP and E4SMA)

| Technology | | Criteria | | | | |
|---|---|---|---|---|---|---|
| | | Level of maturity | Response timeframe | Political commitment | Difficulty of implementation | Cloeseness to consumers |
| Supply | **TPP (hard coal)** | 🟢 | 🟡 | 🔴 | 🟢 | 🔴 |
| | **TPP (lignite)** | 🟢 | 🟡 | 🔴 | 🟢 | 🔴 |
| | **CCGT** | 🟢 | 🟢 | 🟡 | 🟢 | 🔴 |
| | **Pumped hydro PP** | 🟢 | 🟢 | 🟡 | 🟢 | 🔴 |
| Storage | **Classic batteries** | 🟡 | 🟢 | 🟢 | 🟢 | 🟡 |
| | **NaS batteries** | 🟡 | 🟢 | 🟢 | 🟡 | 🟡 |
| | **Flow batteries** | 🟡 | 🟢 | 🟢 | 🟢 | 🟡 |
| | **CAES** | 🟡 | 🟢 | 🟡 | 🟢 | 🟡 |
| | **Supercapacitors** | 🔴 | 🟢 | 🟢 | 🟡 | 🟡 |
| | **Flywheels** | 🟡 | 🟢 | 🟡 | 🟢 | 🟡 |
| | **SMES** | 🔴 | 🟢 | 🟢 | 🟡 | 🟡 |
| | **Fuel cells/hydrogen** | 🔴 | 🟢 | 🟡 | 🟡 | 🟡 |
| Demand | **DM in industry** | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 |
| | **DM in households and services** | 🔴 | 🟢 | 🟡 | 🟢 | 🟢 |
| | **EVs** | 🔴 | 🟡 | 🟡 | 🟡 | 🟢 |
| | **PtG** | 🔴 | 🟢 | 🟢 | 🟡 | 🟢 |
| | **PtH/C small boiler** | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 |
| | **PtH/C small HP** | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 |
| | **PtH/C large scale IND** | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 |
| | **PtH/C large boiler DH** | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 |
| | **PtH/C large HP DH** | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 |
| Legend | 🟢 | high | short term | high | low | achievable |
| | 🟡 | medium | medium term | medium | medium | uncertain |
| | 🔴 | low | long term | low | high | not applicable |

This section has provided a comparison of a number of options to provide additional flexibility to the European power system. Traditional flexibility options are certainly the most mature and economical options, and this is the main reason why flexibility was provided in power systems almost entirely by controlling the supply side. However, the increase in intermittent RES capacities is leading to higher flexibility needs, as i) intermittent RES increases supply side variability and uncertainty, increasing the need for flexibility; ii) intermittent RES displaces part of the conventional generation capacity, tending to reduce the availability of flexible resources on the system.

In this context PtH/C options seem to perform quite well. These applications make use of mature technologies such as electric boilers, heat pumps and storage tanks. These technologies are scalable from large to small sizes, and they are generally cost competitive compared to other flexibility options presented in this section. Generally, electric boilers are the less capital-intensive solution and work quite well in a context of low electricity prices. On the other hand, heat pumps have the advantages of converting power more efficiently and allowing (in some cases) the flexibility of producing both heat and cold. For end users the benefits of installing PtH/C applications mainly relate to the potential fuel cost savings associated with the heat generation with traditional systems as well as periods of low electricity prices. Similarly, for local heat suppliers (i.e. providers of district heating) the benefits of PtH/C relate to cost savings associated with a lower usage of boilers and/or cogeneration plants in low electricity price times. The next section will demonstrate the existing and possible future business models using these technologies.

# IV. BUSINESS MODELS

In general, when talking about business models for PtH/C technologies, there are two different categories – business models for large-scale units and business models for small-scale units (e.g. for households). Business models for large-scale units should be based on capturing the benefits of network services, which can be provided for transmission system operators. For small-scale units, business models should enable direct benefits through adequate rates and regulations (e.g. hourly billing). Several existing business cases are described in the following.

The topic of flexible production and storage was studied in a previous Insight_E Policy Report [56], particularly with regard to business models and legislation.

For T&D (transmission and distribution) storage, three main business models are outlined:

- system operator owns the storage asset and captures network value only,
- system operator owns the storage asset and captures both network and market values,
- a third party owns the asset and captures network and market value.

From the perspective of large-scale PtH/C technology operators, which can provide network services, the most interesting is the latter business model, where the asset is owned by an independent party, who can be registered as a generator and/or a consumer on the market. The transmission or distribution network operator has a contractual agreement with the asset owner to benefit from network services. Expenses of the transmission or distribution network operator then qualify as OPEX (operating expense) and can be recovered through the fee charged for using the network. The third party keeps the control of the asset and can optimize the use of the system according to its own interest (market operations, etc.) as well as the requirements of the distributor.

The marketing of PtH/C flexibility is suitable both for the residential and the industrial sector. Three general concepts to market the flexibility in the current market setting are distinguished - marketing via the spot market, marketing via the control reserve market and usage for network services.

In addition to that, the generated heat can be marketed in several ways - depending on the PtH/C installation itself and its surrounding heat consumers. The heat could either satisfy the heating and hot water demand of buildings, i.e. the heat is fed-in into a local or district heating network, or satisfy industrial heat demands. According to specific requirements, several technical solutions are available.

In the following sections, different business models for PtH are presented and analysed. Firstly, the relatively mature business model of marketing via the German reserve energy market is presented and explained, followed by two PtH-based pilot projects in Germany and Denmark, which aim at the exploitation and marketing of small-scale PtH flexibilities.

## IV.A. Existing business models

### Marketing via the reserve energy market

To balance the grid frequency variations due to temporary power plant outages and feed-in fluctuations, transmission system operators have load-frequency control concepts. The transmission system operators (TSOs) tender required control reserve capacities. In Germany, there are three different qualities primary control reserve, secondary control reserve and minute reserve, whereby the former two consist of both positive and negative reserve capacity. Primary control reserve has to stabilize network frequency within 30 seconds. The nature of PtH applications enables them to be used as secondary control reserve. The capacity in secondary control reserve has to be able to be started up to full power within five minutes. The capacity is offered to the transmission system operator, who can activate the capacity according to its needs to balance forecast errors and unplanned outages. To guarantee a transparent and efficient market procedure, the tendering is conducted via an internet platform and market results are published. In the German market setting, the minimum lot size for secondary control offers is 5 MW

, the increment for higher offers is 1 MW. When flexibility is marketed via the control energy market, energy from the installation can be requested by the transmission system operator to stabilize the network. In situations with higher renewable energy feed-in (i.e. negative control energy is needed), the nature of PtH makes it possible to store or use the excess of energy in the form of heat.

The revenue streams for the control reserve consist of two different parts – the power price and the energy price. The power price is paid only for the provision of control reserve whereas the energy price is paid for the activated amount of energy. The provider is compensated both for the provision as well as for the use of its flexibility.

The presented business model is exploited on a large scale in Germany, e.g. by Enerstorage [57] or TWL (Technische Werke Ludwigshafen) [58]. In 2015 TWL installed a 40 MW PtH installation, which is marketed via the control energy market and moreover connected to its district heating network. Enerstorage is a company specialized in projecting and marketing industrial scale PtH installations. In the last years they developed a business model similar to the one presented above and realized multiple PtH installations at industrial sites like Stadtwerke Neumünster, K&S and Südzucker.

However, the above explained business models are only for industrial-scale installations. Small-scale PtH installations (e.g. decentralized installations) can only exploit this business model if they are organized and controlled in a pool.

### “Flexible Power-to-Heat” pilot project

A second way to market flexibility from PtH is via the spot market. In 2013, the German energy supplier EnBW and the distribution system operator in the same region NetzeBW started pilot project “Flexible Power-to-Heat” [59] to test and assess the feasibility of a business model based on marketing via spot market. The general idea of the project was to exploit decentralized flexibility potentials on the end consumer side. Storage heating systems and heat pumps in the residential sector are considered favourable technologies as they are widely spread and have a relatively high power to be controlled. By adding smart measurement and control units and linking the multiple heating devices, the capacity in the residential sector is pooled and can provide flexibility, which is contracted then by energy traders or generation companies. Taking into account forecasts for wholesale market prices, weather and thus the renewable energy feed-in and grid usage, an operational plan deploys the flexibility in a better way. Generally, the flexibility can be used by the energy supply companies to integrate renewable energies and to react on price fluctuations on the spot market. For the customer side no significant shortcomings regarding the heating service quality are expected.

With large renewable energy generation and a high density of storage heating systems and heat pumps, the town of Boxberg in Germany was identified as being favourable. In total 2.4 MW of flexible PtH loads were contracted from 150 households, requiring a different marketing strategy as the 5 MW required for the control reserve market are not met. The first project evaluation showed promising results, both consumers and the involved companies agreed on a continuation of the project. Unfortunately, the exact revenue streams or economic viability indicators were not published by EnBW.

The pilot project has proved the feasibility from a technical point of view, on the monetary side tariff models for end consumers still need to be developed. However, one of the project's results is that central control by the operator is necessary and that individual time-flexible tariffs for end customers are not applicable, as a simultaneous feed-out would lead to a grid overuse. The grid overuse issue was solved applying a "quota system", limiting the feed-out of each PtH installation with a simultaneity factor. The benefits like reduction of electricity purchase costs and reduced grid usage could be parsed to customers. However, the exact tariffs for end consumers and balancing methods are still in development. As a time-variable tariff is not feasible due to grid constraints, one possible option could be a credit on the customer's electricity bill, which compensates for the corresponding benefits.

A second concept considered in the pilot project is the use of the flexibility for grid purposes, i.e. distribution system operators (DSO) use the flexibility to avoid and counteract critical grid situations, especially in regions with high renewable energies feed-in. Again, decentralized flexibilities can be exploited on the end consumer side and controlled with smart measurement and controlling devices. If the DSO detects a (local) grid overload due to feed-in of renewable energies, it can increase the feed-out using the PtH flexibilities.

In this way, the curtailment of renewable energy generation as well as the amount of grid expansion necessary to integrate the augmenting share of renewables can be reduced, which decreases the long-term system integration costs and leads to a more efficient energy system. The resulting tariff structures for the customers still need to be developed, possible options might be a tariff with power and energy price similar to the one paid for reserve energy or a corresponding credit on the electricity bill of the end customer.

However, to roll out this business model on a mass-market scale, further development is required. On the one hand, the measurement and control technology is not mature for the mass market yet. On the other hand, the regulatory framework is not favourable for end consumers to provide flexibility due to taxes and fees on fed-out electricity. An exemption or a completely changed regulatory framework for small-scale flexibilities is required to make concepts like "Flexible Power-to-Heat" feasible on a mass-market scale. In comparison to industrial-scale flexibility providers, small-scale installations have to bear all the additional price components, which is not always appropriate. For example, in a grid overuse situation the consumption of the PtH installation contributes to the smooth grid operation and the integration of renewable energies, hence an exemption from the taxes and fees could be justified.

**"Control your heat pump" pilot project**

A project aiming at a similar business model is conducted in Denmark, where Energinet.dk, the Danish transmission system operator, launched a pilot project in 2010 with 300 households replacing their oil-fired heating systems with controllable heat pumps [60]. These heat pumps are mainly used to integrate the large share of fluctuating wind energy in the Danish energy system. According to Energinet.dk, the currently installed 80,000 heat pumps in Denmark could provide 120 MW of flexible load in the long term.

Together with multiple project partners (Intelligent Energistyring, ArosTeknik, Neogrid Technologies, LIAB, Exergi Partners, the Danish Technological Institute, EURISCO, Grundfos Sensor and Insero) an IT platform was launched [61]. The pilot project has an open-source structure, both from the hard- and the software side.

If time-variable tariffs are applied for the end consumers, the augmented electricity consumption in times of high wind feed-in (equal to low electricity prices) supports the smooth grid operation. The end customers profit from the low energy prices and short pay-back periods (heat pumps compared to oil-fired heating systems), the energy system profits from the supply-oriented demand. In contrast to the project “Flexible Power-to-Heat”, where all installations are in one town, the installations in this project are widely spread in Denmark, i.e. a grid overuse due to simultaneity is not an issue. However, this project is also not on the mass-market scale yet and further developments are required. Again, the regulatory framework is crucial to the success of the business model, as a high share of the end customer price consists of state-induced price components. Project partner Insero identifies clear price signals from the markets, flexible network tariffs and tax reliefs for system-serving energy consumption as essential drivers for the success of the project.

Similar to the project presented above, the pilot project proves the technical feasibility, but uncovers further problems and obstacles that have to be solved and overcome, if residential PtH should serve the system integration of renewable energies on a large scale.

### “Sunstore 4” pilot project

The IEA report on heat and electricity systems [62] builds on real case studies from a selected range of applications, technologies and locations to analyse the impact of existing barriers and opportunities against these technologies. The case studies analysed in this report include industrial cogeneration applications and three DHC (district heating and cooling) systems, of which one DHC system includes a heat pump and a thermal storage. The Sunstore 4 project is a district heating plant located in Marstal, Denmark that was developed to demonstrate the production of 100% renewable-based district heating and flexible management of different intermittent energy sources with the assistance of thermal storage. The plant combines solar thermal energy, a biomass boiler coupled with an Organic Rankine Cycle (ORC), a compressing heat pump (1.5 MW) and thermal storage. The Sunstore 4 plant was conceived as a demonstration of a 100% renewable energy system for DH that is flexible and can deal with the challenges related to an intermittent generation from solar. The storages and heat pump system also provide possible power system benefits beyond the network. For example, electricity can be converted into heat and stored during periods of high wind power production or can offer additional economic benefits when electricity prices are low. Regarding financing mechanisms and business structure, total investments for the Sunstore 4 plant were 15.5 million EUR with 4.1 million EUR in support from the European Commission and project financing with a municipal guarantee for 100% of the investment. The interest rate for the loan is 3.05% for a 25-year annuity loan. Yearly maintenance is approximately 50,000 EUR, and the expected payback period is less than 10 years (including the support). Marstal DH is a consumer-owned cooperative, and more than 95% of buildings in Marstal are customers with possibility for additional customers to join the network free of charge. Marstal DH has applied this policy to attract more households, thereby reducing the costs of the Sunstore 4 project and annual maintenance by economies of scale. Typically, new customer installations are revenue positive after four years. The heat price for customers is a combination of a fixed price based on the size of the building and a variable price, which is determined based on annual consumption. Metering is wireless and payment is per kWh consumed. Finally, Sunstore 4 produces heat at roughly 50-60 EUR/MWh, which is considerably lower than previous DH production prices of 70 EUR/MWh from heat produced using bio oil.

The business case for PtH in the Sunstore 4 project show that for better profitability PtH/C technologies should be combined with other technologies or storages.

**Simulation of possible business models**

Report [24] evaluates the potential for PtH applications in the context of the Dutch market. The assessment starts with an evaluation of the current and future developments in the Northwest European electricity markets, as electricity prices are a critical driver of the business case for PtH technologies. Potential business cases are presented in combining PtH technology with an existing combined-heat-and-power (CHP) installation or a gas-fired boiler. The business case for PtH in the Netherlands is based on an evaluation of costs and benefits and estimated return-on-investment in today's market as well as for 2023 market simulations, assuming incremental levels of installed PtH capacity. For these calculations, several basic assumptions regarding the capital structure were applied (debt/equity 80%/20%, interest 5.5%, required return on equity 15%, economic lifetime 15 years). Since a sizable segment of the investment costs involve costs for grid connection, the evaluation distinguishes between the situations where a new grid connection is required, as well as the situation where a grid connection is present for existing combined-heat-and-power installations. The results indicate that the case is highly constrained under current conditions. In case no grid connection is present, costs for PtH applications are likely to outstrip the benefits. Only marginal investment in PtH capacity on sites with existing grid connections for existing combined-heat-and-power installations may break-even. Only if prices fall well below the simulated prices, can the investment be expected to be profitable.

## IV.B. Possible future developments of business models and required policy framework

As seen in the sections above, there are several ways to market PtH flexibility. In all possible marketing options, flexibility serves for the integration of renewable energies into the existing energy system – be it on the level of the transmission grid, the distribution grid or on the level of a better market integration.

Based on all presented business cases, it can be concluded that policy and financing support has a great influence on PtH/C project economics. In addition, capturing the benefits of network services should be enabled through contract with transmission system operator or other stakeholders in the power system. For small-scale PtH/C technologies, it is essential to establish adequate rates and regulations to capture the benefits of changes in electricity prices over time. Generally, PtH/C technologies achieve better profitability when combined with other technologies or storages.

The establishment of adequate business models is essential for broader deployment of PtH/C technologies in the sense of providing flexibility. It is necessary to develop a framework which will anticipate all potential obstacles and thus foresee the right mechanisms. Due to the fact that each power market is specific, it is necessary to develop business models for PtH/C technologies for each country, i.e. power market with their own specifics. Business models should be progressive enough to anticipate the needs of the future. Namely, in order to foster further deployment of PtH/C technologies in the sense of providing flexibility it is necessary to stimulate producers of such technologies to improve their products to be ready to participate in the power market as active players. However, it is necessary, in parallel with technology development, to stimulate end users to buy such products. End users must be aware of the benefits they can gain if they would buy a technology, which is able to actively participate in the power market. Each country must develop adequate legal and technical frameworks, which would stimulate manufacturers to start producing such, so-called smart products. Moreover, it is necessary to impose at the very beginning that such smart products have enough room for deployment in the future. In other words, it is necessary to anticipate possible requirements on these products in the future, for instance duplex vertical and horizontal communication, remote control, compatibility with other technologies, etc. In addition, to stimulate end users to accept such smart technologies, they need to know why they should buy products, which are more expensive than conventional no-smart products.  For instance, hourly billing is one way, but still there is a question whether this measure is sufficient or some additional measures are needed. Moreover, the importance of PR measures should not be underestimated. The aforementioned prerequisites are presented in the Figure 29.

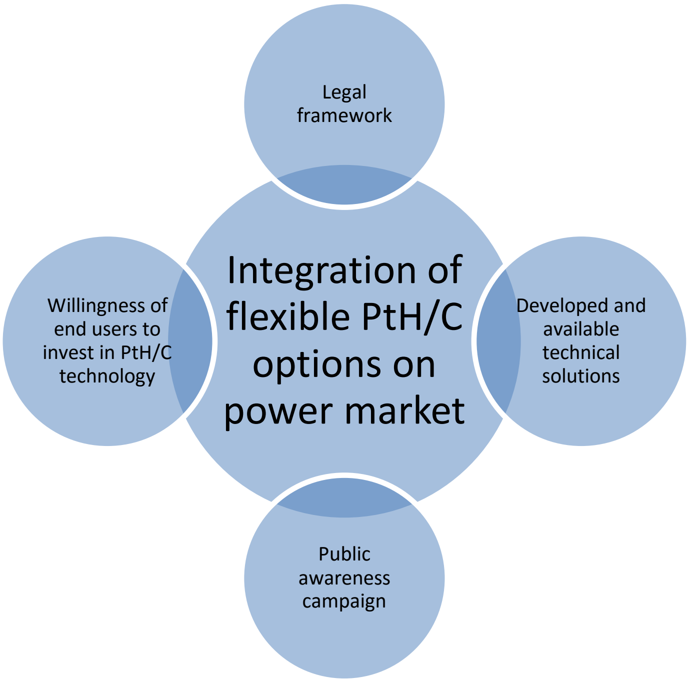

Figure 29: Conditions for deployment of business model for PtH/C technologies

In order to deploy flexible PtH/C options, i.e. technologies which would be able to support the power system, a holistic approach is needed. It is necessary to develop simultaneously all the aspects of PtH/C integration, such as technical, legal, social and economic ones. It is necessary that policy makers gain insight and perceive the importance and potential, which PtH/C options have for the future power system characterised with a lot of intermittent renewable energy sources. It is also necessary to align the objectives of investors with those of society, in order to fulfil the full benefit and potential of PtH/C options.

With demonstrated applications on the industrial scale as well as applications in the residential sector like heat pumps and storage heating systems, a market potential for PtH is given. Multiple business models and concepts are developed and tested. Whereas for industrial scale PtH marketing opportunities already exist and are economically viable, small scale PtH requires further development to be rolled out widely. This development consists not only of technological and IT development in terms of pooling and smart controlling, but as well of a development of the regulatory framework. The pilot projects show the technical feasibility and uncover further requirements.

Changes like the exemption from fees and taxes or adapted grid usage fees, that reflect benefit for the energy system, are necessary to open the market for residential sector and end consumers. As Götz et al. [22] point out, the economic viability of residential PtH installations is strongly influenced by the state-induced electricity price components. Hence, the future success of small-scale PtH is essentially dependent on the regulatory framework. A coupling with other flexibilities on the demand side like e-mobility and battery storage applications should be considered as well, especially due to the high seasonality of heat demand in the residential sector.

The next sections will discuss the potential for Power-to-Heat/Cool applications, assessing the future excess electricity (low electricity price) across Europe, quantifying the potential of PtH/C applications, and identifying the regulatory framework needed to incentivize such applications.

# V. POTENTIAL DEVELOPMENT OF POWER-TO-HEAT / COOL IN EUROP0E

Europe is determined to involve flexibility from the demand side (including PtH/C) to reach its climate and energy targets. In particular, the Energy Efficiency Directive [63] explicitly urges EU national regulatory authorities to encourage demand-side resources "to participate alongside supply in wholesale and retail markets", and also to provide balancing and ancillary services to network operators in a non-discriminatory manner [64]. The latest assessments from [65] indicate that Belgium, Finland, France, Ireland, Great Britain and Switzerland have reached a level where demand-side response (DSR) is a commercially viable product. In Sweden, the Netherlands, Austria and Norway demand response companies are being established, but significant regulatory barriers remain an issue. In the remainder Member States, demand response is either illegal or its development is seriously hindered for all market participants due to regulatory barriers. Denmark, Germany and Italy are conducting regulatory reviews and this status may change in 2016. However, Poland and Spain do not seem to be taking the required steps at this stage; this may be caused by limited regulatory resources or particularly intractable barriers. Figure 30 provides a graphical overview of the current level of development of DSR mechanisms.

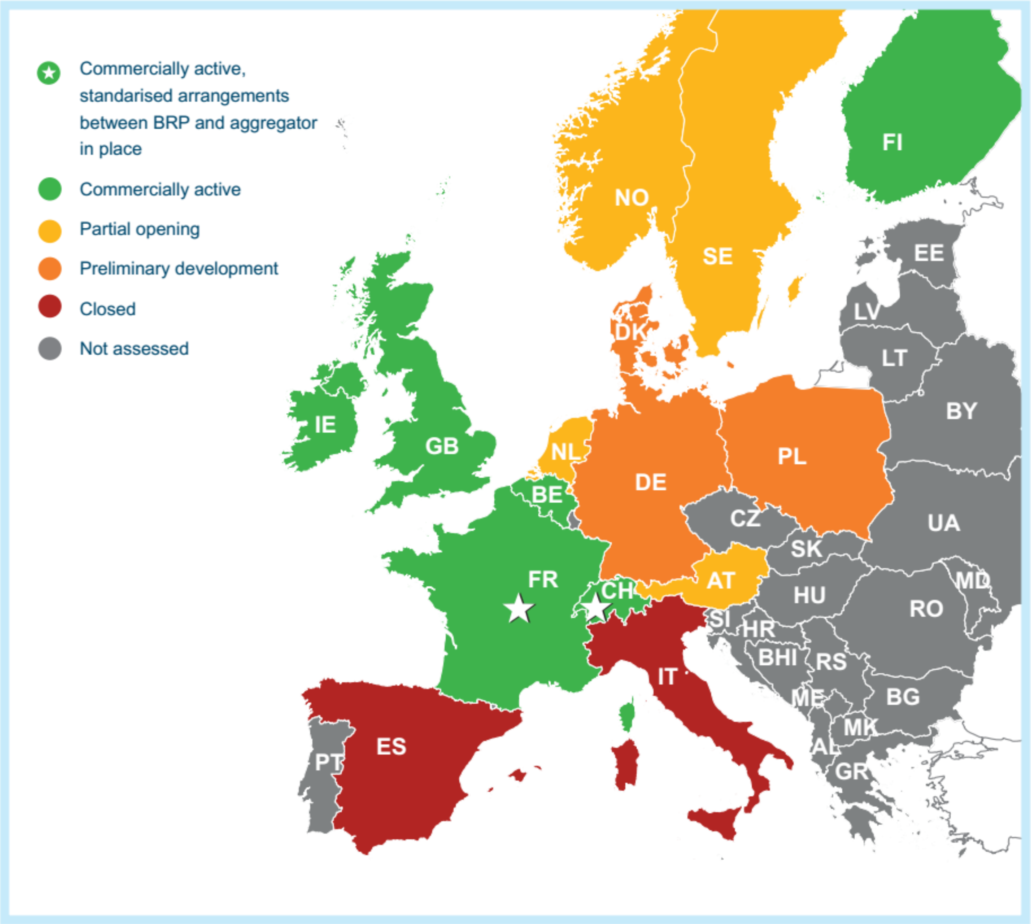

Figure 30. Demand response development map of Europe 2013-2014 [65]

Although the policy mechanisms in the same countries are still lacking, a number of studies have shown that demand response technologies, and in particular PtH/C applications, have a relevant technical potential across EU, even these estimates still show a high level of uncertainty.

## V.A. Literature based overview of the potential development for PtH/C in Europe

This section reviews the current state-of art of research on quantifying which potential is foresee in the current and future European energy markets and presents an overview of foreseen total European potentials and some specific assessment for some selected countries. A number of studies have shown that PtH/C have a relevant technical potential across Europe, even if these estimates still show a high level of uncertainty.

With growing in-feed from intermittent renewable energies, the need for flexibility rises. One main source of future flexibility is the demand side. Only a few studies take demand response into account when they quantify future developments, mostly in sensitivity calculations. This section reviews current available studies for the EU.

At European level, analysis from Gils [5] has quantified substantial theoretical demand-side response potentials in all consumer sectors. Aggregated over all European countries and consumers, the hourly average load reduction potential through shedding and delaying is estimated to 78 $GW_{el}$. Similarly, the overall load increase that can be achieved by advancing demands is in average around 216 $GW_{el}$. Restricting to PtH/C applications this potential reduces (on average) to 29 $GW_{el}$ for load reduction by shedding or shifting to a later point in time, and 96 $GW_{el}$ for load increase by shifting to an earlier point in time. Table 13 demonstrates the average potentials for load reduction and increase in PtH/C applications, subdivided by country.

More recently, modelling assessments from the International Energy Agency (IEA) [66] estimate that currently demand-side response could be technically applied to almost 20% of the annual electricity demand (~ 600 TWh in the EU), shifting demand to different periods within the same day. The report indicates that such potential varies greatly by region and sector, but in all regions most of the current and future technical potential at lower overall cost (upfront and opportunity costs) lies in the buildings sector, especially in space and water heating and cooling, namely PtH/C applications.

Other modelling analysis from the IEA Energy Technology Perspectives 2016 [67] foresees the specific PtH capacity potential in the EU to reach about 100 $GW_{el}$ by 2020 and over 150 $GW_{el}$ by 2030.

Table 13: Average DSM potentials of PtH/C applications, subdivided by country in $MW_{el}$, based on [5]

| | load increase PtC in $MW_{el}$ | load increase PtH in $MW_{el}$ | load reduction PtH/C in $MW_{el}$ |
|---|---|---|---|
| **Austria** | 48 | 1416 | 431 |
| **Belgium** | 105 | 1556 | 649 |
| **Bulgaria** | 33 | 922 | 340 |
| **Croatia** | 19 | 294 | 229 |
| **Cyprus** | 8 | 49 | 104 |
| **Czech** | 49 | 1554 | 411 |
| **Denmark** | 52 | 967 | 386 |
| **Estonia** | 9 | 236 | 66 |
| **Finland** | 60 | 4121 | 376 |
| **France** | 550 | 15553 | 4191 |
| **Germany** | 450 | 13414 | 4480 |
| **Greece** | 65 | 1079 | 976 |
| **Hungary** | 39 | 1273 | 436 |
| **Ireland** | 40 | 986 | 207 |
| **Italy** | 341 | 8761 | 3946 |
| **Latvia** | 10 | 345 | 67 |
| **Lithuania** | 5 | 468 | 92 |
| **Luxembourg** | 5 | 78 | 37 |
| **Malta** | 2 | 23 | 45 |
| **Netherlands** | 161 | 2474 | 940 |
| **Poland** | 152 | 4878 | 1304 |
| **Portugal** | 55 | 1043 | 527 |
| **Romania** | 38 | 2749 | 520 |
| **Slovakia** | 23 | 958 | 249 |
| **Slovenia** | 9 | 275 | 100 |
| **Spain** | 337 | 4449 | 3790 |
| **Sweden** | 96 | 7516 | 755 |
| **UK** | 347 | 15463 | 2843 |
| **Total EU28** | 3109 | 92900 | 28497 |

Separate estimates via a custom top-down approach[13] from Sia Partners [68] quantified the current (2012) European DSR potential at 800 TWh, of which 10% for residential space heating (i.e. PtH), 4% for residential water heating (i.e. PtH), 2% for residential air conditioning (i.e. PtC); 10% for tertiary space and water heating (i.e. PtH) and 2% for tertiary air conditioning (i.e. PtC). This is equivalent to a reduction peak capacity potential of 52.4 $GW_{el}$, i.e. to about 10% (9%) of the peak load estimated by ENTSO-E by 2020 (2025) [69]. Of this potential about 19.7 $GW_{el}$ are accounted to PtH/C applications in the residential and services sector. In industry, the split between PtH/C and others is not provided.

Estimates of future deployment of DSR in the European context are also available from Bertsch et al. [70]. In their scenario analysis, they assume a DSR technical potential to ranging around 100 $GW_{el}$, of which the largest (about the 80%) from the residential sector. Despite this large technical potential, the developed potential is expected to reach only about 15 $GW_{el}$ by 2020 and about $20_{el}$ GW by 2030. The specific PtH/C potential is not specifically assessed, however the expected DSR development in the services and domestic sector, where most of PtH/C applications lies, is rather small by 2030[14].

Demand-side response potentials per country vary significantly in absolute terms, reflecting the differences in energy consumption. According to [68], the largest potentials are observed in Germany (9,6 $GW_{el}$), France (8,1 $GW_{el}$), United Kingdom (5,8 $GW_{el}$), Italy (5,1 $GW_{el}$) and Spain (4,8 $GW_{el}$). In relative terms, expressed in % of the peak load, DSR potential represents around 7,5% for most countries, even for some countries (Belgium, Greece, Spain, Luxembourg, Slovenia, Slovakia and Finland) may reach on average more than 10% of peak demand. Crudely applying the same proportion of PtH/C across countries across regions[15], a first approximation result of PtH/C potential may be estimated. The theoretical PtH/C capacity potential relies at 3.6 $GW_{el}$ in Germany, 3 $GW_{el}$ in France, 2.2 $GW_{el}$ in the United Kingdom, 1.9 $GW_{el}$ in Italy and 1.8 $GW_{el}$ in Spain.

A separate literature assessment from Ecofys [71] shows the results of different studies as well as their assumptions on the shiftable demand in the peak hour of the country. The comparison showed in Figure 31 underpins i) the differences in potentials between countries, and ii) the high level of uncertainty on estimating these potentials.

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[13] The starting point of this assessment is the estimation of the industrial, tertiary and residential electricity consumption. The total consumption per sector is then disaggregated across the main processes, and in a next step, processes with DSR potential are isolated for analysis. Typically, these are processes with storage possibilities or inherent thermal inertia. Further calculations assessed the electricity consumptions for each process, and the installed capacities per process. Based on this approach the capacity guaranteed at peak is then evaluated. For baseload processes, the average load factor is applied. Corrections for seasonal patterns, weekly patterns and daily patterns are also applied. Finally, available capacities at peak are multiplied with the reduction potentials per process. Total DSR potential is finally obtained by summing up all processes.

[14] About 20% of total DSR development

[15] i.e. about 38% of DSR potential across Europe

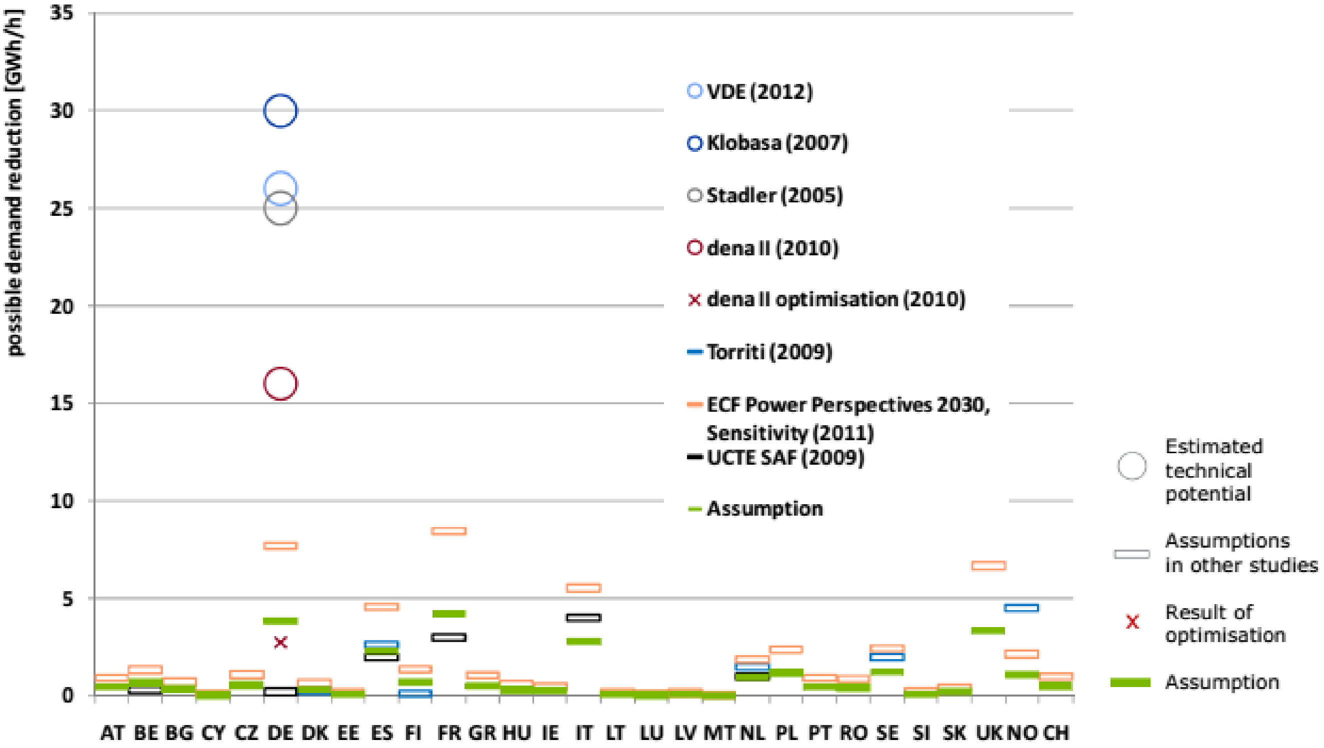


Figure 31. Overview of assumptions and results on DSM potential from different studies [71]

More detailed country-specific studies and analysis are available in literature. Some key findings for relevant MS are presented in the following sections.

### *V.A.1.i Denmark*

With a share of around 39% wind in its total electricity consumption in 2014, Denmark is the world's leader in wind deployment. The Danish energy system is moving towards an entirely renewable based generation by 2050 and the installed wind capacity will continue to increase in the future. The independence from fossil fuels in electricity generation and heating is expected to be reached even earlier [72]. Therefore, a sophisticated demand-side management is intensively considered. Increase in thermal demands are positively correlated with higher wind speeds. In addition to this, Power-to-Heat solutions seem to be more applicable in Denmark due to low potential of pumped storage plants. The country's political agenda and the goal of the Danish TSO is to foster the integration of heat pumps and electric boilers at CHP plants in district heating[73].

A detailed assessment of the existing Danish Power-to-Heat capacities and the future potential is analysed in a study by Agora Energiewende [72]. In 2014, installed wind and PV capacity in Denmark amounted to roughly 5 GW and 0.56 GW, respectively. Considering that Denmark has a total net transfer capacity of 6.4 GW to Germany, Sweden and Norway and its peak demand is 6 GW, exporting the excess electricity to neighbouring countries is one of the solutions in hours of electricity surplus. A part of Danish excess electricity can be stored in Norway's hydro power plants and another part could be consumed in Germany. However, over the past years the number of wind parks in the northern part of Germany increased significantly. Thus, the utilization of the 2.4 GW transfer capacity to Germany is strongly depending on the wind conditions in the northern part of Germany.

Besides, Denmark has a large number of CHP plants, which nearly provide 75% of the total district heating supply. Regulations in the last decade incentivized the reduction of electricity production and increase heat production in times of high wind electricity generation. CHP plants and electric boilers in district heating systems get tax discounts on generated heat. Therefore, in low or negative price hours the district heating companies are incentivized to "bypass" the steam turbines of their CHP plants or to shift the load from CHP plants to boilers. When prices on the electricity market increase again, the plants can switch back to cogeneration mode quickly. However, heat pumps are currently excluded from this regulation. Today, only electric boilers play an important role in the market for ancillary services.

The regulatory framework also includes market prices for CHP plants to secure the investments. As a compensation for low electricity prices in the spot market, the CHP plants are subsidized, independently from their generation.

In addition to these regulations, in 2013 the general tax on electricity used for space heating was reduced in order to increase the number of heat pump installations, replacing gas- and oil-fired boilers.

The existing electric boiler capacity in 2014 amounted to around 0.4 $GW_{el}$ in district heating. The Danish transmission system operator "Energinet.dk" expects that the electric boiler capacity increase to up to 0.52 $GW_{el}$ by 2020. Today, the main driver of investments is the ancillary service market. The investment for electric boilers is 0.7 million € per MW which is relatively low. Therefore, electric boilers are profitable with less than 500 full load hours per year. "Energinet.dk" states that electric boilers will mainly be used for peak shaving and ancillary services in the future. The study also forecasts the additional expansion in electric boilers will not be higher than 1 $GW_{el}$ until 2030, although the average load is around 4.3 $GW_{el}$ and peaks are twice the average load.

In contrast, heat pumps are considered to play an important role in the future Danish energy system mainly because it is possible to obtain around three times the consumed electricity in form of usable heat. Heat pumps can be applied in both individual heating and district heating, providing base or intermediate load. Heat pump investments are around 1.5 million € per MW which is relatively high. Assuming that 20% of district heating load is supplied by heat pumps operating at 4000 full load hours, the future development is estimated to be around 0.6 $GW_{el}$ in Denmark with an average load of 0.3 $GW_{el}$. However, only four large heat pumps have been operating in district heating systems in 2014. Under the current regulatory framework, heat pumps cannot compete with biomass-based technologies such as biomass boilers that pay no taxes or biomass CHP plants which receive a feed-in premium. The current trend in Denmark is to invest in biomass applications rather than heat pumps.

The oil demand for individual heating purposes in Denmark is approximately 3.9 TWh. Assuming that all oil heating systems are replaced by heat pumps with a coefficient of performance (COP) of 3, the required electricity demand amounts to 1.3 TWh, corresponding to an average base load of 150 $MW_{el}$. Taking into account peak demand situations and fluctuations this potential capacity increases up to 1.5 $GW_{el}$. Accordingly, heat pumps in individual houses may contribute to individual heating in the range between 0.15 $GW_{el}$ and 1.5 $GW_{el}$.

The PtH applications in private and district heating sum up to a total capacity in the range between 2.2 and 3.5 $GW_{el}$ in 2030.

In addition to that, assuming 25 % of the relevant load (more than 1.6 $GW_{el}$) comes from heat pumps, the capacity of heat pump installations for process heating is estimated to be around 0.4 $GW_{el}$.

Another study by K. Hedegaard and M. Münster [74] analyses the Danish electricity market and investigates in particular how individual heat pumps can influence the Danish energy system until 2030. Three main scenarios are analysed with the perfect foresight optimization model Balmorel, which optimize investments in power/heat production, storage and transmission capacities as well as the operation of the system. In the first scenario "NOiHP" neither investments in individual heat pumps nor in individual storage technologies for heat pumps or heat accumulation tanks are allowed. The second scenario "iHP" permits investments in individual heat pumps. In the third scenario "iHP-Flex", not only investments in individual heat pumps but also in storage technologies and heat accumulation tanks are possible.

The comparison of the scenarios NOiHP and iHP shows the impact of individual heat pumps on the energy system. Comparing the scenarios iHP and iHP-Flex reveals the effect of investments in heat storages complementing the heat pumps, thereby facilitating flexible operation. The results show that the capacity in the NOiHP scenario for heat pumps in district heating is more than 2.2 $GW_{th}$. In the other scenarios, the increased investment in individual heat pumps reduces the investment in district heating heat pumps to around 1.6 $GW_{th}$. If investments in individual heat pumps are an option, all individually heated areas are covered by heat pumps, even if no investments in flexible storage utilities are available. This results in a substantial electricity demand of 4.3 TWh. The option to invest in heat storage technologies provides only moderate system benefits and investments to heat accumulation tanks are identified to be not competitive.

Another publication [73], which is part of the stoRE project, summarizes the prediction of the Danish TSO energiet.dk as follows. The capacity of electric boilers will possibly increase up to 400 $MW_{el}$ until 2017 and then remain stable until 2030. In the same period, the installed capacity of central heat pumps will increase up to approximately 500 $MW_{el}$. Until 2030, the expansion of individual heat pumps is estimated to be roughly 900 $MW_{el}$, mainly installed in rural areas, where district heating infrastructure is not available. As a result, the PtH installations sum up to a total amount of 1.8 $GW_{el}$ in 2030.

Table 14 summarizes the presented publications regarding the PtH potential in Denmark. It can be stated that the PtH potential is relatively low considering the large share of fluctuating wind feed-in in the Danish energy system. This is mainly due to the regulatory framework and concurring technologies (particularly biomass-fired boilers), which face more favourable conditions. However, the different publications identify a potential within the range of 1.6 and 3.5 $GW_{el}$ for the year 2030.

Table 14: An overview over the presented publications for the PtH potential in Denmark

| Authors | Approach | Estimated PtH potential (until year) |
|---|---|---|
| **Agora Energiewende [72]** | Development of electric boiler and heat pump capacity plus replacement of oil for heating purposes | 2.2 – 3.5 $GW_{el}$ (2030) |
| **Hedegaard and Münster [74]** | Analysis of scenarios with perfect foresight optimization model Balmorel | 1.6 – 2.2 $GW_{th}$ (2030) |
| **future expectations from Energinet.dk (Danish TSO) [73]** | Development of electric boiler, large-scale heat pump and small-scale heat pump capacity | 1.8 $GW_{el}$ (2030) |

### *V.A.1.ii Germany*

In Germany, the amount of electricity generation from renewable energy sources has risen significantly in the past years. In 2015, the production from renewable energy sources represented 29% of the total gross electricity generation [75] and the curtailment of renewable sources amounted to roughly 4.75 TWh [76]. For the purpose of balancing the fluctuations of RES electricity production, there is already an existing capacity of 0.5 $GW_{el}$ of large-scaled PtH installations in Germany. Installations bigger than 5 $MW_{el}$ can only offer secondary control power in the control energy market to increase their revenues. Götz et al. [77] draws the conclusion that Power-to-Heat facilities, which can provide secondary negative reserve power, can amortize in less than one year. This business is considered as profitable as marketing the generated heat.

The existing PtH systems are dimensioned in 10% and 40% of maximal thermal load. Due to the increasing number of hours with negative prices in the spot market, Prognos AG recommends in a Power-to-Heat system in the dimension of 30% to 50% of the maximum heat demand [78]. With this approach, the technical potential for Germany is calculated between 7 $GW_{el}$ (30% of maximum district heat demand) and 11.7 $GW_{el}$ (50% of maximum district heat demand).

In some studies, the technical potential is determined by the same approach. The usable heat demand that is provided by the heat sink is named as technical potential on the supply side. Furthermore, the technical potential is also limited by the excess electricity which causes negative prices in the spot market and this potential is named as technical potential on the demand side.

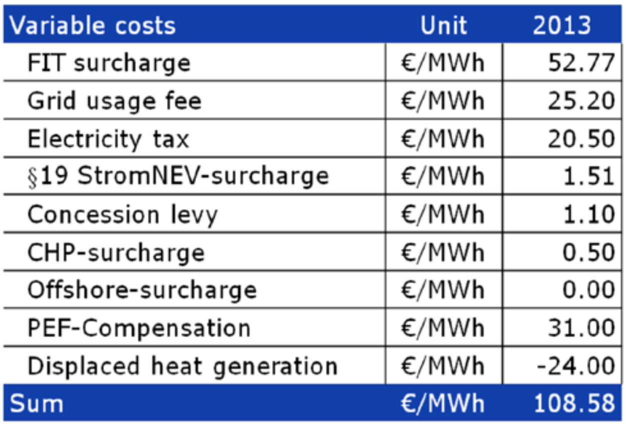
In 2013, Böttger et al. published a study [21] evaluating the technical potential of Power-to-Heat technologies in district heating grids for the years 2015 to 2030. In these analyses, the aggregated technical potential in district heating on the supply side is identified to be between 9.4 $GW_{el}$ (30% of maximum district heat demand) and 16 $GW_{el}$ (50% of maximum district heat demand). However, the potential on the demand side, i.e. the negative residual load, limits that potential to 5.8 $GW_{el}$. Due to the increasing number of hours with negative electricity prices, Böttger et al. identify a technical Power-to-Heat potential of 20.6 $GW_{el}$ for the year 2030.

In another study [77], Götz et al. calculate the technical PtH potential for the operating region of 50 Hertz, one of Germany's transmission system operators. The maximum theoretical potential for PtH in this region amounts to 11.8 $GW_{el}$, which is the maximum district heat demand in the region.

The technical potential of PtH is calculated to be between 2.2 $GW_{el}$ (20% of maximum demand) and 5.6 $GW_{el}$ (50% of maximum demand). The technical potential on the demand side, i.e. low or negative residual load, is 5.5 $GW_{el}$ in 2014 and 7.8 $GW_{el}$ in 2020. The residual load is estimated to be negative for about 700 hours in 2014 and for more than 2500 hours in 2020.

This study also concludes that PtH installations are not profitable for heat provision on the spot market. PtH installations need a high extent of negative spot market electricity prices. For a PtH installation connected to a district heating grid the variable costs can sum up to 108.58 €/$MWh_{el}$ in 2013 (see Table 15). Especially the Feed-In-Tariff surcharge (EEG-Umlage), the grid usage fees, the electricity tax and the compensation of the primary energy factor (PEF) cause high variable costs for PtH technologies.

Table 15: Variable costs of PtH in Germany for the year 2013 [77]



| Variable costs | Unit | 2013 |
|---|---|---|
| FIT surcharge | €/MWh | 52.77 |
| Grid usage fee | €/MWh | 25.20 |
| Electricity tax | €/MWh | 20.50 |
| §19 StromNEV-surcharge | €/MWh | 1.51 |
| Concession levy | €/MWh | 1.10 |
| CHP-surcharge | €/MWh | 0.50 |
| Offshore-surcharge | €/MWh | 0.00 |
| PEF-Compensation | €/MWh | 31.00 |
| Displaced heat generation | €/MWh | -24.00 |
| Sum | €/MWh | 108.58 |

After determining the technical potential, the perfect foresight model called "P2H" is used to calculate the economic potential. This model optimizes the dispatch of district heating and CHP systems using the technical PtH potential, hourly prices produced by the MICOES-Europe model and historical control power prices from 2010 as input data.

The results show that the frequency and extent of negative wholesale power prices are not sufficient for PtH plants to be economically viable due to the high variable costs. However, if the model also incorporates revenues from control reserve market, the installed PtH technologies are able to generate high returns. The study concludes that a wide exemption from state-induced charges must be debated to secure economic viability.

In a different study [79], Böttger et al. focus on the effects of PtH plants to abolish the must-run generation of base load power plants for control power provision. In hours with low prices, the provision of negative control power leads to must-run generation by base load power plants. PtH technologies in district heating can provide negative secondary control power in these hours, which reduces $CO_2$ emissions and increases the integration of fluctuating renewable energy sources into the energy system.

Figure 32 shows the limitations of thermal power plants providing reserve control power to the grid. Thermal power plants can only vary their generation between a maximum ($P_{max}$) and a certain minimum ($P_{min}$). Plants providing positive reserve capacity must run at least at their $P_{min}$ and plants providing negative reserve capacity must operate at $P_{min}$ plus the provided negative control reserve capacity (necessary must-run generation).

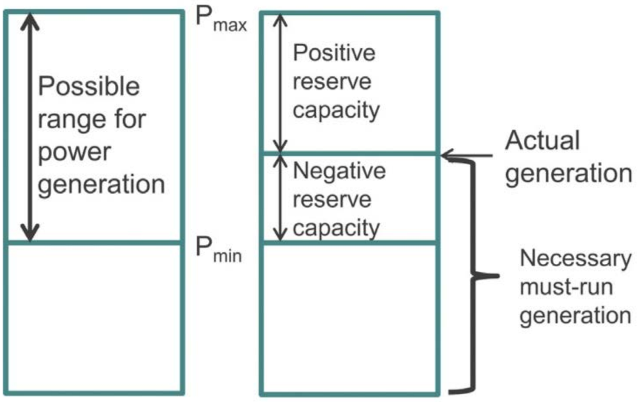


Figure 32: Limitations of conventional power plants for reserve capacity provision [79]

The plants participating in the secondary control market need to maintain their capacity for one week because the bidding periods last one week, which is longer than accurate forecasts can predict weather conditions. As a result, must-run capacities cause more $CO_2$ emissions and have to produce electricity in times where prices are not sufficient to cover the variable costs.

Electric boilers can provide negative reserve power in a cost-efficient way. The modelling results of the control electricity market show that in the year 2023, 1000 $MW_{el}$ PtH can save 158 million € (without considering the installation costs) and up to 1.8 million tons of $CO_2$ emissions in Germany.

In 2012, the annual costs for the provision of negative secondary control power for 1000 MW was estimated to 123 million €. However, the total installation costs are 58 million €. Thus, the installation can amortize in a period shorter than one year. The annual costs for the installation are much lower and the investment costs will decrease in the course of years.

Another study [80] from Forschungsstelle für Energiewirtschaft e.V. analyses and assesses the flexibility options via functional energy storage from a system perspective. For the analyses, a linearized unit commitment model of Germany and Austria is used to perform simulations on the transmission level. The study concludes that PtH in district heating systems and flexibility of the load in industrial processes provide the largest benefit on the transmission level. The installed capacity of PtH technologies amount up to 10 $GW_{el}$ and their full load hours is roughly 1200.

However, the analyses considering the taxes and fees show that barely any PtH expansion are applied. Therefore, adaptations for the allocation of primary energy factors in district heating and time variable tariffs (e.g. varying the fees temporally for system beneficial behaviours) are recommended. After a regulatory framework adaptation, the flexibilisation of small-scale devices like heat pumps, night storage heaters and electro mobility can also play an important role.

A study [81] from Agora Energiewende focuses on the cost-efficient use of PtH applications and the required policies to incentivize these applications. Three different use cases for PtH-application are identified and investigated. In addition to this, a direct current power flow model of Germany splitting the country into 18 regions is set up to analyse the economic potential.

In the first use case, PtH reduces the conventional must-run capacity because conventional power plants no longer need to stand by to provide a backup capacity. Instead, PtH technologies provide negative control reserve, which also reduces the prices in the control energy market. This market provides investment security to the PtH applications because of its high and secure returns.

In the second use case, PtH applications are used to reduce curtailments caused by regional congestions in the grid. In the past years, there has already been a lot of curtailment in the northern part of Germany, especially in the federal state of Schleswig-Holstein. Thus, the regional focus of the study is set on the northern part of Germany, particularly on the city of Hamburg and the federal state of Schleswig-Holstein. Power curtailment of renewable sources due to the grid congestions in Schleswig-Holstein in 2012 amounted to 346 GWh, which is about 3.5 % of the annual RE-generation in Schleswig-Holstein. This equates to 37 million € per year.

The PtH devices can reduce this supply-sided surplus which cannot be transmitted because of grid congestions. However, today the direct use of this curtailed electricity by PtH applications is not possible, because high state-induced charges have to be paid on top of the wholesale electricity market prices. Thus, the study recommends the implementation of a local market for PtH applications, where only electricity is marketed, that would have been curtailed otherwise. For the local markets, in which the number of the actors is not sufficient, a minimum price can be introduced to avoid market distortion. The study also proposes to tender a pilot project in order to gain some experience beforehand for these markets.

In the third use case, PtH devices consume electricity in times with negative residual load and resulting negative electricity prices on the spot market. These surplus situations will occur more often in the future. Unfortunately, the use of electricity in these hours is only economic for PtH applications below prices of minus 7 ct/kWh. Like other PtH studies one of the policy recommendations is to reduce the state-induced charges for PtH applications to consume electricity that would be otherwise curtailed. The proposed price for making PtH devices economic is minus 2 ct/kWh.

In addition to the presented use cases the study calculates the PtH potential for the city of Hamburg, the federal state of Schleswig-Holstein and for entire Germany. In the city of Hamburg and the federal state of Schleswig-Holstein, there is a big difference in technical PtH potential between summer and winter, the potential in summer is estimated to 0.5 $GW_{th}$ in contrast to 2.5 GW in winter. Peak potentials can be up to 4 $GW_{th}$.

For the calculation of the economic potential, in a first step 4700 hours of negative residual load in 2023 in Schleswig-Holstein are forecasted using the renewable feed-in patterns of 2011. In 2023 there are 3000 hours, in which a surplus of generation cannot be transported to the other regions in Germany or exported to neighbouring countries because of interconnection limitations. All the surpluses sum up to around 2.7 TWh. Even though the investment of electric boilers and fix costs of PtH devices are not so high, it is not economic to absorb whole surplus. The new investments are only economic after 800 full load hours. Therefore, PtH devices can use 2.3 TWh of these 2.7 TWh economically, which represents a maximum capacity of 1.3 $GW_{el}$ for Schleswig-Holstein alone.

The national-wide excess electricity is calculated using the renewable feed-in patterns of 2010 and 2011. 2010 was a year with below-average wind conditions, whereas in 2011 the wind speeds were slightly higher than average. For the weather conditions of 2010 and 2011 there are 2.2 TWh and 4 TWh of excess electricity in 2023, respectively. PtH devices in Germany could consume up to 2.8 TWh of the identified excess electricity in 2023.

The presented studies for Germany show that there is a business case with high returns for PtH applications such that they are already profitable in Germany. However, making profits on the wholesale energy market or using PtH devices for direct consumption of otherwise curtailed electricity is not possible by today. Consequently, policy adaptations need to be debated widely and profoundly.

Table 16 provides an overview over the presented publications in this section. PtH is identified to play a key role in the German heating sector in the future. Especially for the provision of flexibility to integrate the growing share of renewable feed-in in the German energy system and in combination with the existing district heating infrastructure, PtH installations are considered to be economically viable even today. The majority of publications use approaches, which consider both the supply side (supply for heating demand) and the demand side (demand for flexibility). As a key technology in the future district heating provision, the technical potential of PtH amounts up to 16 $GW_{el}$ in 2030.

Table 16: An overview over the presented publications for the PtH potential in Germany

| Authors | Approach | Estimated PtH potential (in year) |
|---|---|---|
| **Böttger et al. [21]** | Supply side: 30 – 50 % of maximum district heating demand | 9.4 - 16 $GW_{el}$ (2015) |
| | Demand side: negative residual load limit | 5.8 $GW_{el}$ (2015)<br>20.6 $GW_{el}$ (2030) |
| **Götz et al. [22]** | Supply side: 20 - 50 % of maximum district heating demand | 50Hertz area alone:<br>2.2 - 5.6 $GW_{el}$ (2015) |
| | Demand side: negative residual load limit | 50Hertz area alone:<br>5.5 $GW_{el}$ (2014)<br>7.8 $GW_{el}$ (2020) |
| **Prognos Germany [36]** | Supply side: 30 – 50 % of maximum district heating demand | 7 – 11.7 $GW_{el}$ (2010) |
| **Forschungsstelle für Energiewirtschaft e.V [80]** | Economic analysis without considering taxes and fees | 10 $GW_{el}$ (2030) |
| **Agora Energiewende [81]** | Economic analysis for the federal state Schleswig-Holstein and Germany in three different use cases | Schleswig-Holstein alone:<br>1.3 $GW_{el}$ (2023)<br>Germany:<br>up to 2.8 TWh/year (2023) |

### V.A.1.iii Austria

Austria has a large amount of hydropower and biomass sources because of its topology. In 2015, 73% and 5% of Austria's electricity generation originates from hydro and biomass power plants, respectively. With a share of 87% of renewable energy sources in the electricity mix of 2015, Austria is among the countries with the largest renewable shares in Europe [82]. Due to its topological conditions, the country is also favourable to pump storage power plants. In 2012, the total installed pumped storage capacity amounted to 4.3 GW and the total capacity of planned projects until 2020 were roughly 3.5 GW [83].

In Austria, district heating is common in densely populated regions and infrastructure exists in many places. In 2015, 24% of residential heating was provided by district heating and the final consumption from district heating in Austria amounted to roughly 77 PJ, of which 47% came from renewable sources [84] [85].

PtH installations for district heat provision are currently growing in Austria, mostly as supplement to existing cogeneration plants. Decreasing electricity wholesale market prices foster many projects throughout the country. In Salzburg, two PtH installations larger than 10 MW were put in operation for district heating since 2015, as supplement to existing gas cogeneration plants [86]. In Hall, a 20 MW PtH installation is supposed to be put in operation in the autumn of 2016 to supplement the existing biomass cogeneration plant [87]. The installed capacity of PtH installations in Austria is still very low, but shows a large increase in the past two years and further development potential in the future.

A study [88] under contract of Ministry for Transport, Innovation and Technology of Austria analyses different flexibility options between electricity and heat sector. Due to a lack of available studies for Austria, the potential for Austria is estimated based on available data for Germany. In this study, the proportional relations between Germany and Austria in district heating consumption, final energy consumption and in the population are assumed to be 1:6, 1:8 and 1:10, respectively. Other relevant parameters are as well estimated applying a proportional relationship to Germany. As a basis for this calculations a German study [78] published by Prognos was used. Prognos estimates the district heating PtH potential for Germany to 11.7 $GW_{el}$ installed capacity (50% of maximum district heat demand) and required storage volume to 110 $GWh_{th}$. Downscaling this data to Austria results in a potential PtH capacity of 2 $GW_{el}$ and installation of 18,3 $GWh_{th}$ in terms of storage volume. This equates 370.000 $m^3$ of storage volume. The installed storage volume in Austria is already more than 150.000 $m^3$. Consequently 40% of the potential is already exploited.

### V.A.1.iv The Netherlands

The Netherlands is an important energy market in Central Western Europe. The national electricity demand in peak hours amounts to around 17 GW [89]. Generation capacities sum up to roughly 33 GW and consist of a large share of gas-fired power plants (59%) and hard coal power plants (18%). In 2015, installed renewable capacities were 6 GW, from which 59% are wind power plants and 34% are PV capacities, and a further growth is expected in the upcoming years [89].

Considering the ongoing decrease of electricity wholesale market prices, in the near future PtH may compete economically with conventional heating technologies like gas or oil. Estimating and assessing the PtH potential both from the technical and the economic aspect is essential for a profound and expedient discussion. The PtH potentials for the Netherlands are presented and discussed in this section based on a report [24] prepared by CE Delft.

The total heat demand of the Netherlands in 2012 amounted to 1200 PJ, which equates to 40% of the overall Dutch end energy consumption. The heat demand originates almost 45% from industry processes, 30% from the residential sector, 7% from horticulture and around 20% from tertiary sector. Regarding temperature levels, almost two thirds of the heat demand is needed on levels below 100°C. In the following, each sector is analysed regarding its technical potential to deploy PtH.

The heat demand of the residential sector and utilities amounts to a total of $17.4_{th}$ GW peak, from which between 5 and 10 percent can be allocated to district heating. In a conservative estimation, CE Delft only considers large-scale district heating systems as technical PtH potential. Thus, the PtH potential identified decreases to 475 $MW_{th}$. Note that small-scale installations in the residential sector, like heat pumps or storage heating systems, are neglected in this investigation. The seasonal temperature variation strongly influences the heat demand in the residential sector and utilities, lowering the technical potential to around 95 MW in summer months. However, the seasonal variation in demand matches the offer due to higher wind generation (and fluctuation) in winter months.

The greenhouse horticulture sector has an important share in the total heat demand. The annual heat demand of the sector is almost 100 PJ and is due to strong seasonal and diurnal variations (higher demand during the night, mainly in winter months). However, CE Delft states that horticulture has a technical potential for PtH, but do not point out a technical potential in numbers.

The heat demand of the industrial sector is very promising for PtH devices. For the estimation of the technical PtH potential all heat and steam processes with a steam temperature below 250°C are considered, amounting to a total of roughly 130 PJ per year. Using two different approaches, the range of PtH potential is determined. Firstly, assuming a number of full load hours between 6,000 and 8,760 a PtH potential of between 4.1 and 6 $GW_{th}$ is calculated. Secondly, scaling the industrial natural gas demand pattern currently used for heat and steam processes below 200°C to the deployment of PtH for the same purpose delivers a range from 3 to 5.5 $GW_{th}$ – notice, that the second approach only considers lower temperature levels and thus is the more conservative one. However, the seasonal and weekly patterns of the demand have to be respected. On weekdays during winter the maxima are reached, while on weekends in summer the demand and thus the PtH potential is the lowest.

Under conservative assumptions and only considering the residential sector, utilities and the industrial sector, an overall technical potential for PtH between 3.1 $GW_{th}$ in summer and 6 $GW_{th}$ in winter is identified.

In a second step, the economic feasibility of a PtH installations compared to a conventional gas-fired heating installation is assessed using on the one hand electricity prices of the period 2010-2013 and on the other hand electricity prices forecasted for 2023 by a simulation approach.

Apart from the distinction in electricity price levels, there is a distinction between grid-connected and non-grid-connected PtH installations. The yearly costs are decreased by 10 percent, if the grid-connection is already existent (i.e. PtH installation added to an existing combined power and heat (CHP) unit and infrastructure). The structure of the remaining cost components is as follows (no existent grid connection): around 60 percent electricity, 23% network charges, 5% investment, 2% O&M and one percent energy taxes. Comparing the avoided gas costs and the yearly costs of a PtH installation, the economic viability is assessed.

To respect the influence of installed PtH capacity on wholesale market prices, a further analysis with PtH capacities after the installation in the market is conducted for each capacity up to 5 GW. With an increasing capacity of PtH in the market the wholesale market prices increase, which is counterproductive for the economic feasibility of additional installations. Matching this economically viable potential with the technically feasible potential for PtH, CE Delft determines the potential for PtH installations in the Netherlands.

Using the prices of 2010-2013, neither the project with existent grid-connection nor the one without is economically viable. Assuming the electricity and fuel price forecasts for 2023, the economics of both the grid-connected and the non-grid-connected project significantly improve.

In the case where a grid connection has to be newly installed, CE Delft identifies a potential of 500 $MW_{th}$ of PtH to be deployed profitably in 2023. The more favourable case of an already existing grid connection reveals an economically profitable potential of 2.5 $GW_{th}$. Considering the 2.8 $GW_{th}$ installed CHP capacity in the Netherlands, this potential might be exploited [24].

To summarize this section, it can be stated that there is a significant PtH potential in the Netherlands: surely from the technical and very likely from the economical point of view. The identified PtH potential of 2.5 $GW_{th}$ is a significant potential to increase the flexibility in Danish electricity system considering the 17 $GW_{el}$ peak electricity load [89]. Furthermore, the seasonal variations in heat demand match the increased wind generation in winter months. Future developments in the regulatory framework might influence the economics and even facilitate new potentials and business models.

### *V.A.1.v France*

Viewed in the European context, France has a relatively large share of electrical heating in the residential sector. Due to the large share of nuclear electricity generation (76% in 2015 [90]), the base load prices are low and thus favourable for electric heating in the building sector. With just 16.8 cents per kWh the electricity price for households in 2015 was roughly half of the price for German households [91]. In 2012, the share of direct electric heating capacities represented roughly 29% of total installed capacities in decentral heating in buildings. Furthermore, heat pumps represent 10% of the total share. 9% is air source heat pumps and the other 1% is ground source heat pumps. The number of installed air source heat pump units and ground source heat pumps are more than 4.9 million and 120000, respectively [43].

With a largely rolled-out retrofit of the residential sector heating towards smart and remotely controllable appliances, the potential in installed electric heating devices might be exploited as flexibility to integrate the volatile and intermittent feed-in of renewable energies.

According to the French TSO RTE, the installed wind and PV capacity in France amounts to more than 16 GW in 2015 [90]. In 2015 the French Parliament adopted an energy transition bill which will initiate a number of significant changes to France's energy landscape [92]. The bill's objectives include a 40% reduction in greenhouse gas emissions by 2030 compared with 1990 levels, with a 75% reduction by 2050. Fossil fuel consumption will be reduced by 30% compared with 2012 levels by 2030, with the share of renewables in final energy consumption increasing to 32% (40% of electricity production). Nuclear capacity will be capped at the present level, with the share of nuclear energy in electricity production falling to 50% by 2025. This transition away from fossil fuels towards a power system based almost entirely around nuclear and renewables by 2050 implies that France will experience very large amounts of excess renewable electricity and/or excess nuclear electricity [93].

Due to the growing share of renewable electricity capacity, the need for flexibility in the energy system becomes an issue growing in importance in France. In addition to that, neighbouring Germany has an even larger need for flexibility. However, in the current situation scarcity situations and resulting price peaks in France are rather caused by temperature than by volatile renewable energies.

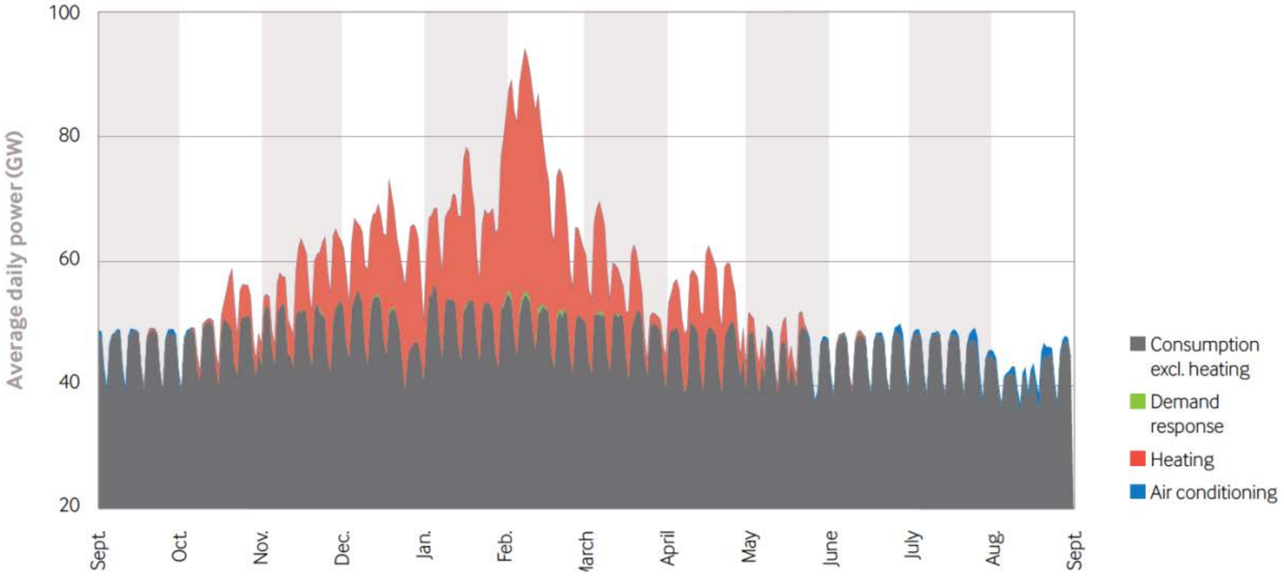


Figure 33: Load curve of winter 2011/2012 showing the temperature sensitivity of French electricity demand [94]

The structure of the French electricity sector leads to specific consumption patterns. As can be seen in Figure 33, the electricity demand underlies a strong seasonal component. According to the annual electricity report of France's TSO RTE, during the winter months of the extremely cold winter 2011/2012 the temperature-sensitivity share in the French load made up to 40 GW [95], not flexible and strongly sensitive to the temperature. See Figure 34 for a detailed illustration.

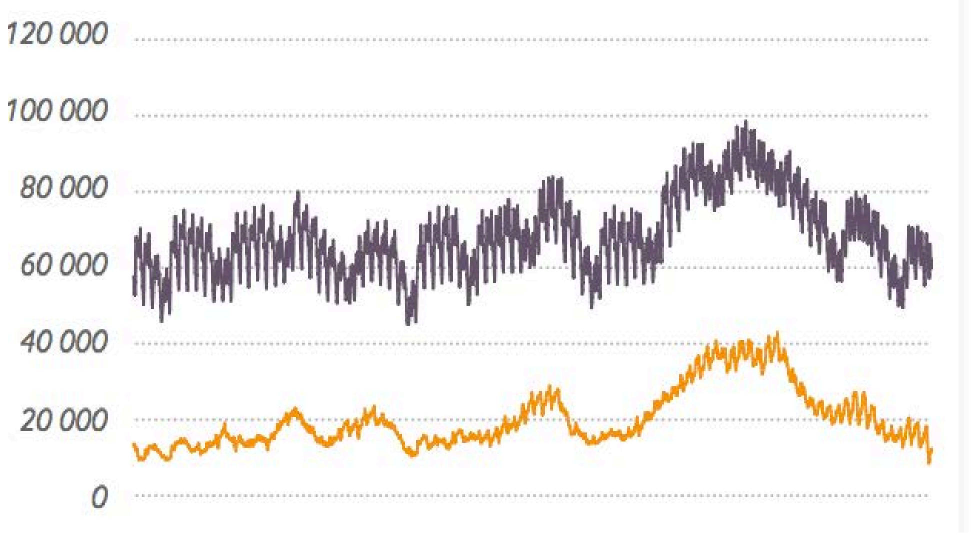


Figure 34: Total French load (purple) and temperature-sensitive share (orange) in winter 2011/12 in MW [95]

However, the winter 2011/12 is considered an extremely cold winter and in other years the peak load of temperature-sensitive load is significantly lower. In the winter 2013/14 for instance the maximum temperature-sensitive share in the load amounted to below 35 GW [90]. Figure 35 shown below underlines this strong sensitivity to temperature with a gradient of roughly -2000 MW/K. In the winter months, the heating demand causes substantial load peaks, whereas during the rest of the year the load remains more or less stable with the typical weekly pattern.

The biggest obstacle to overcome remains the temperature sensitive prices and thus that prices do not fluctuate from one hour to another but rather from one week to another. The electricity demand of PtH appliances with short-term thermal storages can hardly be shifted to times with lower electricity prices, thus small-scale PtH appliances in the building sector are not technically suitable to provide flexibility to the current French electricity system. With a growing share of renewable energies in the system in future, the circumstances tend to improve.

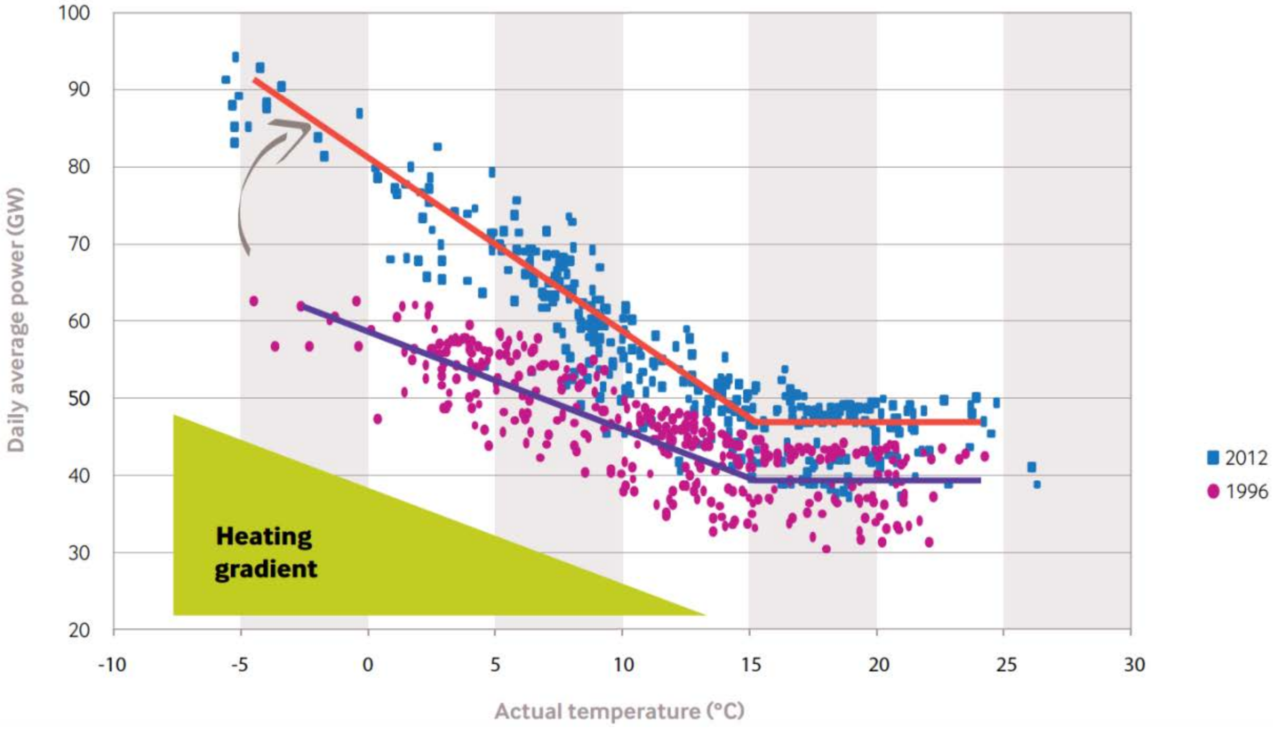


Figure 35: Determination of the heating gradient, 1996 and 2012 [94].

The seasonal pattern is however not favourable for the economic viable exploitation of flexible PtH. On the one hand, despite wind generation tending to be higher in winter months there are as well fluctuations in the renewables feed-in in summer, especially regarding feed-in from PV. PtH with the current demand pattern could not cover these fluctuations. On the other hand, the seasonality lowers the number of operating hours and thus profitability for flexible PtH installations.

On top of that, the occurrence of extremely high temperatures and consequently high electricity prices are not hourly but over several days. Small-scale decentralized heating devices with a short-term storage would typically cost-effective in hourly price peaks, but can hardly help in continuing price peaks.

Taking all these reservations into account, a large-scale rollout of flexible and controllable PtH appliances to exploit flexibility in France is unlikely to happen in the near future. Maybe in the longer term, the expansion of wind and other renewables will lead to more volatile electricity prices in France. The demand will nevertheless remain temperature-sensitive.

It has to be noted, that even if the conditions were favourable, the residential heating sector is an end consumer market. End consumers are very unlikely to retrofit their heating system prior to a breakdown; thus a market penetration would be a tedious process. Generally, the installed capacity in terms of electrical heating is thus very high but as pointed out in the sections above, the circumstances are not favourable for the exploitation of PtH flexibilities.

However, the decentralized capacity market currently implemented in France remunerates the energy suppliers to exploit demand response potentials, in particular PtH, as the supply companies are obligated to prove capacity certificates in the amount of the peak load of their consumers. This mechanism makes exploited flexibility and demand response a tradable asset and might remunerate the exploitation of the small potential that is available.

In this energy landscape, France can be also be considered an important frontrunner regarding demand response developments [64]. Already before sector liberalization, demand response activity was triggered by EDF, both for residential and industrial electricity customers. France had an estimated share of demand response capacity of 1000 MW in 2014. In April 2014, France reduced the bidding values for balancing services from 50 to 10 MW in order to motivate the entrance of smaller entities on balancing mechanisms [96]. Furthermore, RTE, the French TSO organizes an annual tender dedicated to demand response capacities. Since 2014, the NEBEF mechanism in France enables direct trade of demand response in the day-ahead market.

The modelling analysis published by the Institute of Energy Economics at the University of Cologne (EWI) [70] forecasts DSR in France to achieve a capacity of 15 $GW_{el}$ by 2020 and 29.2 $GW_{el}$ by 2030, for the equivalent of 1.89 and 3.29 TWh by 2020 and 2030 respectively.

Focusing on PtH/C, a quantification of the theoretical potential in France is provided by Gils [5]. The hourly average load reduction potential through shedding and delaying is estimated to 4.2 $GW_{el}$, while the overall load increase that can be achieved by advancing demands achieves on average to 16 $GW_{el}$. Separate assessment from Brouwer et al. [97] assumes a technical potential for PtH/C stands at around 4 $GW_{el}$ in France, mostly from space and water heating. These development levels are estimated combining both the theoretical potential from Gils [5], and estimates of deployment by Bertsch et al. [70]. The modelling analysis compared options that can improve the integration of intermittent-RES into future European low-carbon power systems. Results show that demand response lowers total system costs by 2–3%. However, uncertainties regard the cost (costs of load shedding at 200–5000 €/MWh and load shifting at 2–100 €/kW are used) and its limited potential.

### V.A.1.vi Italy

In the recent years, the Italian electricity market has been characterized by a rapid growth of renewable generation and by a decrease of electricity consumption. Non-hydropower renewable energy production capacity increased very sharply, especially between 2008 and 2013. Wind and biomass power generation capacities multiplied by two during this period, while in 2011, installed photovoltaic capacity boomed as a result of the generous prices offered under national subsidies, although it slowed down after 2013 after certain incentives to solar farms on agricultural land were eliminated. In 2015 renewable electricity production delivered about 33% of domestic electricity production; of which 17.1% from hydropower, 13.7% from solar and wind, and 2.1 from geothermal [98]

Contextually, electricity demand has been declining in recent years (-6.9% in the period 2008-2015) [99]. This is largely due to the economic crisis, although a 5% decrease since 2005 can be attributed to improvements in electric generation performance, as well as the active adoption of numerous energy efficiency measures (i.e. fiscal, white certificates, etc.) [100]. Despite decrease in demand, the electricity bill rose sharply between 2010 and 2012 before levelling off in 2013. The general tendency of electricity prices to rise for final consumers is mainly driven by grid costs and increasing taxes to support renewables development, as well as additional measures to promote energy efficiency. Furthermore, the energy component of consumer electricity bills is influenced by the peculiar Italian electricity mix, based mostly on gas (57.9% of fossil electricity production in 2015) while the average European mix is influenced predominantly by nuclear and coal.

On demand side, Italy enjoys a good level of technological advancement, with leading programs such as smart metering, an essential element of demand side management. However currently Italy relies mostly on hydro and gas for its flexibility needs, while the framework for consumer participation in the balancing market is not yet in place. The only exception is the interruptible contracts programme, which is a dedicated demand response programme separate from the balancing market. The enrolment of interruptible loads is currently about 4 GW, with a minimum size of 1 MW to participate [65]. The possible opening of balancing products to demand-side resources could lead to an increase of load participation and given the current high electricity price context may represent an interesting business opportunity for industrial and domestic end-users.

However, given the high uncertainty driven by the absence of clear policy mechanisms, only few assessments to date about technical potential for demand response mechanisms and in particular for PtH/C applications are available. The modelling analysis published by EWI [70] indicates DSR in Italy to achieve a capacity of 7.1 $GW_{el}$ by 2020 and 14.9 $GW_{el}$ by 2030, for the equivalent of 1.29 and 1.98 TWh by 2020 and 2030 respectively.

Estimates of the theoretical potential of PtH/C applications in Italy relies on Gils [5]. The hourly average load reduction potential through shedding and delaying is estimated to 4 $GW_{el}$, while the overall load increase that can be achieved by advancing demands achieves on average to 9 GW. Separate analysis from Brouwer et al. [97] indicates that the technical potential for PtH/C ranges around 3 $GW_{el}$ in Italy, Switzerland and Austria, mostly from space and water heating. The detailed split between single countries is not provided.

### V.A.2. Potential for heat pumps in the decentralized heating sector in Europe

A major potential for flexible PtH in Europe comes from heating and cooling in the building sector. One of the key technologies are flexible heat pumps (flexible HP), as they are considered very efficient and have a mass market potential. With the ongoing development of RE expansion, the characteristics of wholesale electricity prices are favourable for heat pumps as the general level of prices decreases, while there are negative and positive price spikes. In the following section, three publications assessing European potentials for heat pumps (HP) are presented and analysed. The first study was prepared in 2013 by Ecofys, a German energy consulting company, funded by the European Heat Pump Association (EHPA). The second publication is the “European Heat Pump Market and Statistics Report 2015”, a report which is prepared on an annual basis by EHPA summarizes the recent European developments regarding heat pumps. The third publication was prepared by the Lithuanian Energy Institute and published in 2015.

The scope of the study by Ecofys [101] is to estimate the potential of greenhouse gas reduction, the change in final energy consumption in the building sector and the total yearly costs in the European key markets until 2030 for different heat pump installation scenarios. The focus is hereby set on the potential for decarbonisation of the heating and cooling sector and the potential for heat pump sales rather than on estimating the amount of installed heat pump power. Austria, Belgium, Germany, Spain, France, Italy, Sweden and the United Kingdom are analysed as key European markets.

Ecofys defines three different scenarios for the study horizon until 2030: Current policy implementation (CPI), HP+ and HP++. CPI represents a development, where the current policies on a national and European level are implemented; such that greenhouse gas reduction targets and the share of used RE targets for the building sector are reached. HP+ depicts the development for a heat pump share of 50 percent in all new buildings and of 30 percent in retrofits. HP++ is the most ambitious scenario with a heat pump share of 100 percent in all new buildings and a share of 50 percent in retrofits.

In order to investigate the different scenarios regarding the indicators mentioned above, the building stock inventory of each country is analysed. All buildings in the stock inventory are put into eight different categories in the residential and non-residential building sector (e.g. single-family buildings, multi-family buildings, office buildings, education buildings). For each of the categories and each of the countries the heating, cooling and hot water demand are determined by applying demand patterns and adapting them to national climate conditions.

The resulting demands for heating, cooling and hot water are then matched with suitable heat pump technologies, in order to estimate the demand for heat pumps in the building sector. The results for estimated annual heat pump sales are shown in Figure 36. Depending on the evaluated scenario, the number of sales differs largely. In the most ambitious scenario HP++ the number of HPs sold each year in the studied countries increases to more than three million by 2030. In the HP+ scenario, around 1.8 million HPs will be sold per year. The CPI scenario follows the greenhouse gas reduction targets set by the current policies. The number of annual sales is roughly 900,000 in 2030 being twice as much as the number of sales in 2012.

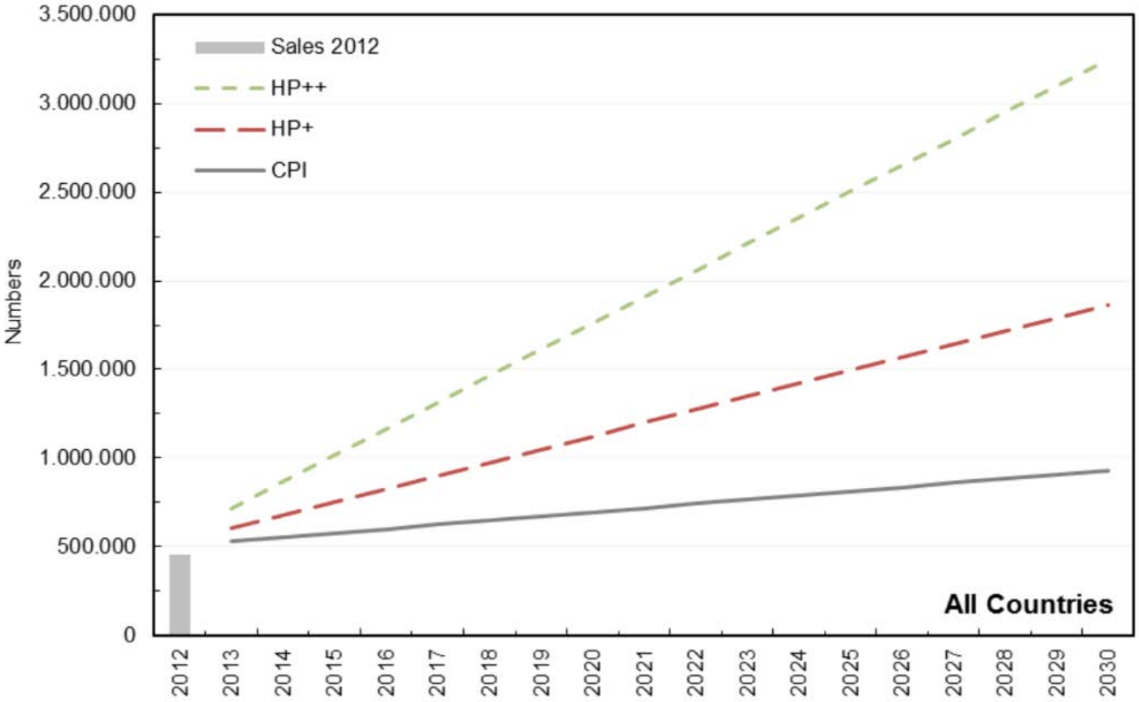


Figure 36: Technical potential of heat pump sales in Austria, Belgium, Germany, Spain, France, Italy, Sweden and the United Kingdom [101]

However, this figure only shows the annual heat pump sales, the study does not disclose the installed heat pump capacity potential. In addition to that, the shown potential sales are normal heat pumps, the penetration of intelligent controllable HP is not analysed in this study. It explicitly stated, that there is a potential for intelligently controlled HP, which are able to react on variable energy prices [101]. However, in the scope of the study such controllable HPs are not analysed and no economical assessment with variable electricity prices is conducted.

For the economical assessment, a Present Value approach is applied taking into account investment-related expenditures, variable energy costs and maintenance costs. The approach does not prove the economic viability in comparison with competing technologies, but calculates the additional costs if the scenarios were realized. The Following parameters are used for the economic assessment.

The maintenance costs for the electric heat pumps are estimated to be 3 percent of the investment per year. The base energy prices are taken from 2010 and an evolution of fuel prices according to energy price trends by European Commission is assumed. The fossil fuel prices are assumed to increase by 2.8 percent each year until 2030. The evolution of electricity prices is divided into four periods: Until 2015 an annual increase of 2.9 percent is assumed, between 2016 and 2020 an annual increase of 2.0 percent, between 2020 and 2025 an annual increase of 0.8 percent and for the timespan between 2025 and 2030 a decrease of 0.3 percent per year is assumed. The electricity price includes taxes only for the consumers which consume electricity below 5000 kWh per year. To calculate the investment-related costs an interest rate of 3.5 percent is assumed. The prices for HP in new installations and retrofits and thus the investments are given in ranges. Depending on the HP technology, the investment is between 530 €/kW and 1870 €/kW. For brine/water and gas-fuelled HP the investment can increase to more than 2000 €/kW.

Regarding the latest developments of the fuel prices, the study's assumptions regarding the fuel price development lead to higher prices than currently observed. The interest rate is assumed to be 3.5 percent. Both assumptions lead to favourable circumstances for heat pumps, as they are capital-intensive (thus a low interest rate leads to low investment-related costs) and competing technologies are fuel-based; thus a high fuel price leads to high variable energy costs for the alternative technologies. On the other hand, for the estimation of the heat pump energy costs, electricity prices for consumers below 5000 kWh per year are used. This consumer group's electricity price contains many state-induced taxes.

However, a sensitivity analysis regarding the interest rate and the price paths could be useful to gain more insights to the relations. A higher interest rate would increase the investment-related cost and thus be unfavourable for the economics of HPs. A different, less increasing path for fossil fuels would decrease the variable costs and thus have a similar effect on the results.

The results published by Ecofys are only partly useful to define the flexible PtH potential. Firstly, as was stated before, only conventional HPs were analysed. Results of an analysis focusing on controllable HPs might differ from the ones presented above. Secondly, the approach to determine the level of penetration of heat pumps in the building sector is rather exogenous not based on economic viability but on strict expansion rules. The scenarios HP+ and HP++ could only be realized, if a European-wide legislation to rollout HPs was forced. To conclude, it can be stated that there is a considerable potential for HPs in the European building sector, which is difficult to quantify.

In the Heat Pump Market and Statistics Report 2015, EHPA presents market data regarding installed heat pumps throughout Europe. The number of sales was more or less stable in the period 2010-2014 (2010: 800; 2011: 809; 2012: 750; 2013: 770; 2014: 797). Since 1995, the installations aggregate to a total of 7.5 million, corresponding to an estimated thermal capacity of 66.3 $GW_{th}$. The largest markets are France, Sweden, Germany and Italy. In 2014, roughly 800,000 heat pumps units with a thermal capacity of about 6.6 $GW_{th}$ were sold in Europe [102].

These figures can serve as a rough estimation for the average power of a heat pump, leading to a capacity of 8.25 $GW_{th}$ per 1 million heat pumps. Assuming the values to be stable over time, the installed thermal capacity for each of the scenarios from the Ecofys study can be estimated for 2030. Underlying a lifetime of 20 years and the sales of the scenarios, the HP++ scenario foresees an installed HP capacity of 318 $GW_{th}$, the HP+ scenario 160 $GW_{th}$ and the CPI scenario roughly 114 $GW_{th}$ of installed HP capacity.

The last publication presented in this section deals amongst others with the heat pumps market development in Europe until 2020. They forecast the projected heat pumps thermal energy to increase by factor 1.8 between 2010 and 2015 and by factor 1.7 between 2015 and 2020. The underlying approach and assumptions are not disclosed. The resulting thermal energy amounts to 84 TWh in 2015 and 140 TWh in 2020. The markets with the largest shares in 2020 are expected to be Italy, the United Kingdom, France, Germany and Sweden [103]. The national values for the thermal energy are illustrated in Figure 37 below.

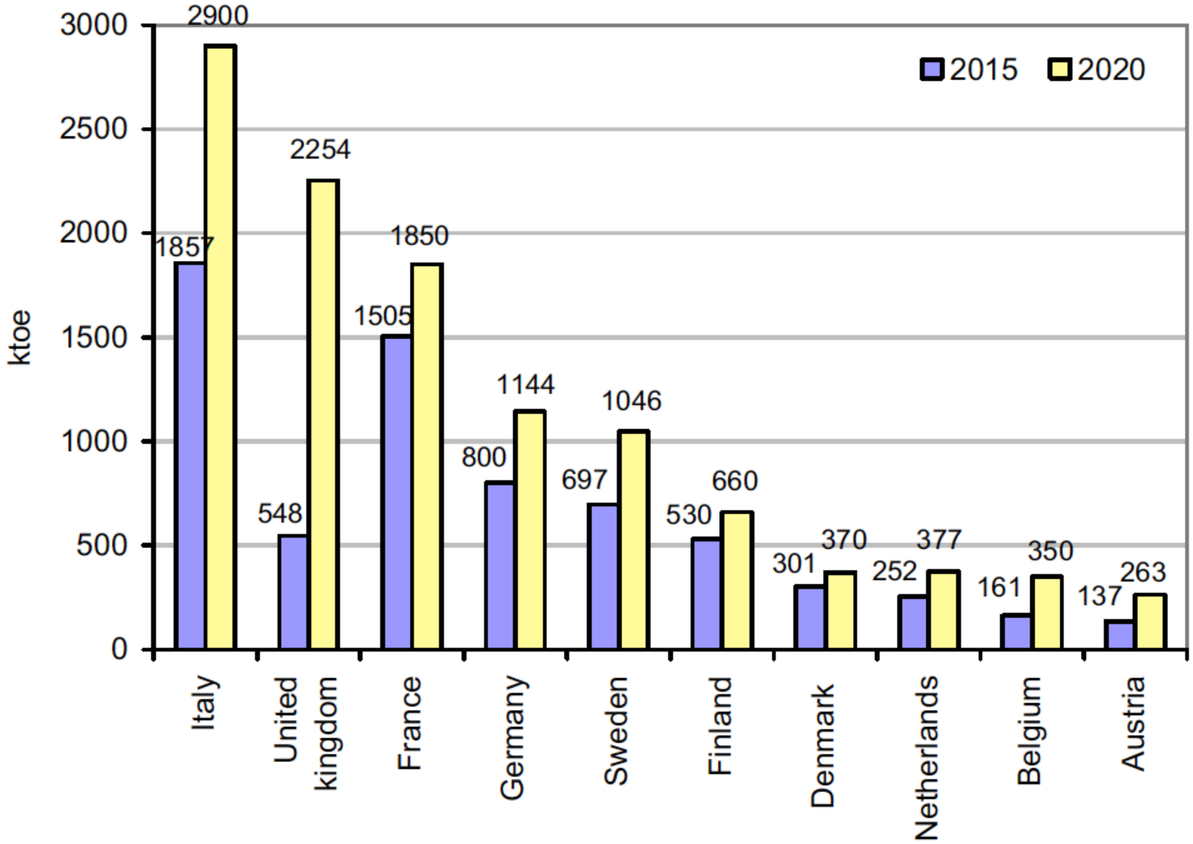


Figure 37: European countries with the largest projected heat pump thermal energy production [103]

However, the underlying assumptions for this forecast have to be scrutinized in order to verify or challenge the results. To conclude, it can be stated that a large growth in the heat pump market is expected which indicates a large PtH potential.

### V.A.3. Evaluating the future excess electricity in Europe

In the European electricity markets, renewable energy systems have preferential treatment in the electricity grid as far as the secure operation of the power system permits. However, there might be times when it is not possible to accommodate all priority dispatch generation, such as intermittent RES as wind and solar, maintaining the safe operation of the power system. These reductions are commonly referred to as “grid-related curtailment”. Additionally another type of curtailment may occur, the so-called “market-based curtailment”. It refers to special situations characterised by a highly inflexible must-run electricity generation in combination with low demand. If market design does not prohibit their occurrence, these situations can be signalled by negative prices. In such situations, the intermittent RES operator or marketer has no incentive to sell his electricity on the market. Negative prices and market-based curtailment affect likewise conventional and renewable power generators. However, the impact on the profitability of renewable power plants is more severe given the differences in their cost structures [104]. Curtailing generation would further cut the revenue potential beyond the limits of the natural potential. Curtailment rates above 4.0% are critical for the economic operation of solar and wind projects while rates above 6.5% almost certainly make those projects uneconomical [105].

As assessed in a previous INSIGHT_E report [106], to date curtailment of intermittent RES in the EU has been largely driven by technical grid security reasons and not economic reasons. However, if renewable policy targets for 2020 and 2030 are met, this may heavily reshape the residual load curves in a number of Member States, as the intermittent RES are expected to play a key role in the realisation of the targets. In case of large wind and solar production, temporary oversupply situations would occur and conventional assets in the system may be unable to react. These contributions may put significant pressure on electricity prices, in which mature techniques, as Power-to-Heat/Cool, seems to offer significant technical potential.

Several studies have provided estimates of future excess electricity in the European market. For the year 2030 several modelling analyses have estimated curtailment levels across Europe. At the EU level Fraunhofer ISI [107] estimates levels of intermittent RES curtailment between 0.6 and 0.8% by 2030 under two alternative electricity demand scenario outlooks. In the longer term (2050) these are expected to grow further to 3.7% to 4.9% respectively. Agora Energiewende [108] identifies power system integration, as a crucial factor for smoothing regional output and mitigating flexibility needs. According to their modelling analysis, the number of hours in which power is curtailed decreases significantly when cross-border interconnector capacities are expanded (41% higher than today). Curtailment reduces from 7217 hours per year (almost every hour of the year) in a case of no interconnection between MS, to 2150 hours in case of system integration. These correspond approximately to 45 TWh and 5 TWh of curtailed generation respectively. The latter is equivalent to a 0.41% of intermittent RES generation curtailment. Both these estimates do not consider alternative flexibility options, such storage plants, power-to-heat/cool options or demand-side management.

Power system integration has been identified as a key element for mitigating flexibility also in [109] and [110]. [109] identifies, under a high RES development scenario by 2030, very high levels of curtailment in insular power systems, such as Ireland (60%) and the United Kingdom (35%). Under this scenario also other countries with large shares of intermittent RES connected to countries with large shares of intermittent RES also, show not negligible levels of curtailment, i.e. Denmark over 10%, the Netherland 8%, Germany and France ~3%. A similar conclusion (but with lower curtailment values) is drawn by Collins et al. [110], who identify potential curtailment issues of delivering a PRIMES Reference scenario by 2030 for isolated power systems such Malta and Cyprus (over than 35% of curtailed intermittent RES electricity), Ireland (over 5% of curtailment), and Portugal (about 1%).

Detailed modelling analysis developed by Greenpeace [105] interestingly states that with similar investment levels in network infrastructure to those already planned by network operators, Europe can cover up to 77% of its electrical load with RES, including up to 860 GW of wind and PV with low (2.9%) curtailment. This may be delivered by preferring investments on the overlay HVDC grid to continued extension of HVAC transmission network, and removing older nuclear and coal inflexible generation. Without doing so, the increase of curtailment is expected to increase by 55% (to 4.5%) and could double or even triple curtailment levels if operators of conventional plant seek to improve their load factors. An overview of 2030 expected curtailment level by scenario is summarized in Figure 38. It is worth noting that the “Energy [R]evolution 2030” scenario already includes the development of further flexibility mechanisms such as electricity storages and demand-side response.

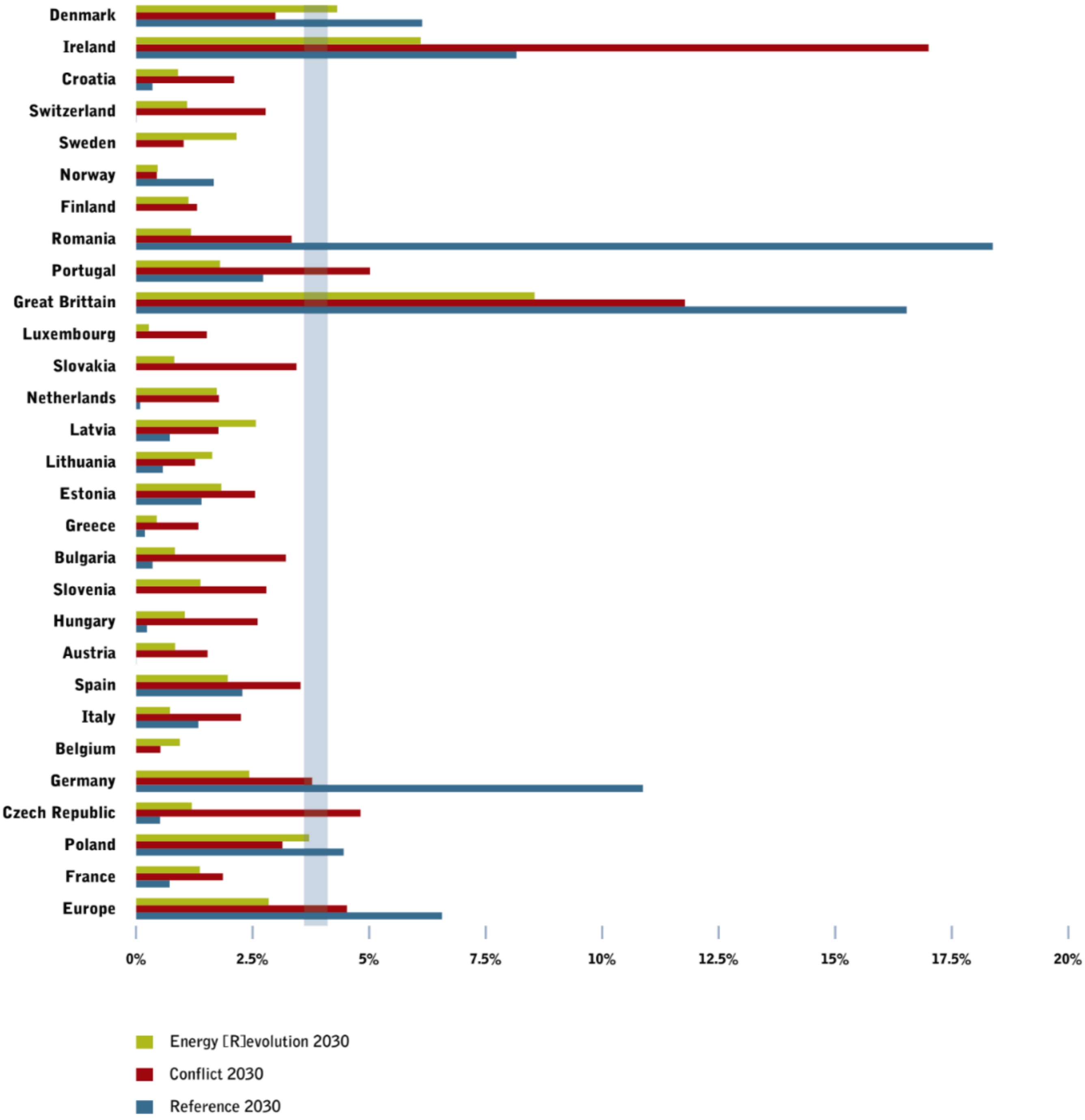


Figure 38. Curtailment rates of wind and solar power from available wind and PV generation by country and scenario for 2030 according to [105]

In the chapter V.B an own assessment for the year 2030 is provided.

## V.B. Towards a quantitative method for the estimation of PtH/C potential in district heating

The previous sections provided an overview of the PtH/C potentials in Europe. Throughout Europe great variations regarding the different countries are identified, especially regarding heating demand and the breakdown of the sectors. The inhomogeneous nature of the European energy system, different weather conditions and the national regulatory frameworks make it hardly possible to estimate PtH/C potential with one common approach. In addition to that, the few publications treating entire Europe are not sufficient for a profound and conclusive estimation. Therefore, in this chapter, national potential assessments for Denmark, Germany, Austria, the Netherlands, France and Italy are calculated with a developed approach. Due to the time limitations, this methodology has some weaknesses, which are also discussed in detail in the following subsections.

The calculation of the technical PtH potential in district heating is assessed using hourly residual load and heat load data. In the first two subchapters, the calculation of the aggregated hourly heat load in district heating and hourly residual load in the electricity system is described, respectively. Afterwards the following two subchapters describe and discuss two different approaches to calculate the PtH potentials in some European countries.

### V.B.1. Calculation of hourly heat load in European countries in district heating

An important factor affecting the hourly heat load in European countries is the outside temperature. Thus, the country profiles should differ regarding the respective climate conditions. Furthermore, the breakdown by the sectors households, industry and trade, commerce and service has a major influence.

For the calculation of the hourly heat load profiles, in a first step, the annual heat demand is distributed to the days of the year for each sector based on the daily temperature data and shares of the sectors in district heating load. Afterwards, the daily heat demand values for different sectors are distributed to the hours of each day using daily standard heat load profiles. As a result, the hourly heat demand profiles for all sectors are obtained throughout the year [111].

In a second step, these hourly sectoral load profiles are weighted with their respective shares of the total demand in district heating and summed up to an hourly country profile. The shares of different sectors in district heating in European countries are derived from the data in [1].

Following Figure 39 demonstrates the aggregated thermal load profile of the district heating grids in Germany.

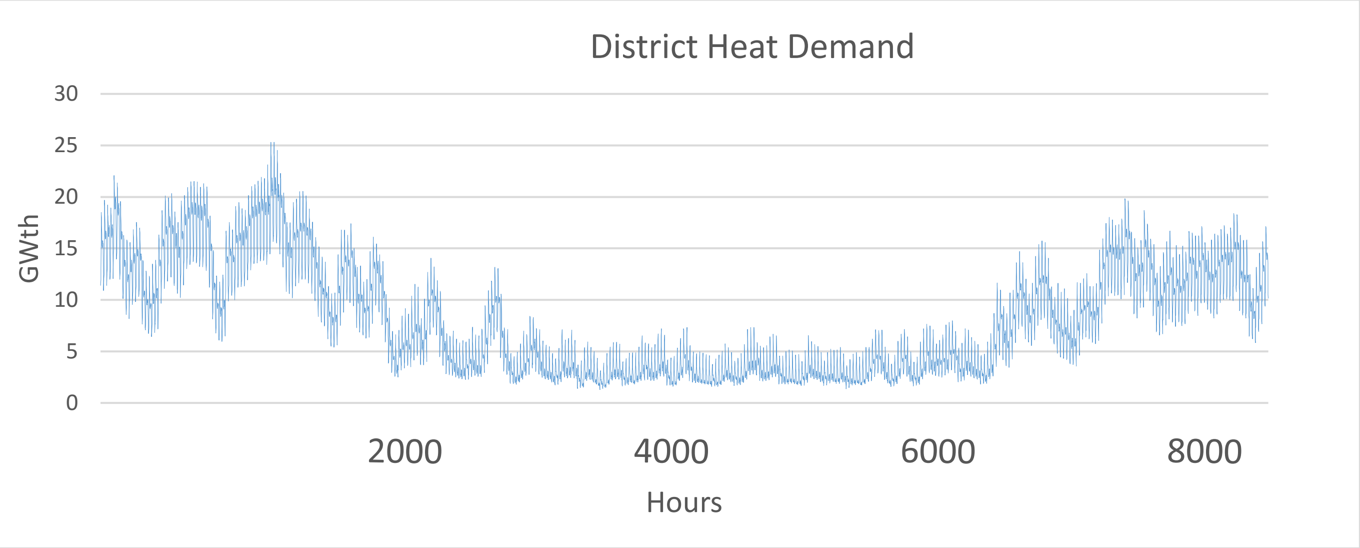


Figure 39: Aggregated thermal load curve of the district heating grids in Germany

The temperature of the capital city is considered as the reference temperature of the respective country. Historical weather data of the European capital cities from 2015 provided by “Weather Underground” [112] are used in the calculations.

Regarding the lack of standard intraday heat profiles for the countries, the existing standard intraday heat load profiles [111] of Germany are assumed to be representative for the other EU countries as well. As mentioned above different intraday profiles for different temperature intervals, sectors and different days of the week are applied. Consequently, temperature differences and the shares of the different sectors in other countries are considered in this approach. However, this simplified approach has some drawbacks that are worth mentioning. The end consumer behaviour in households and tertiary sector can be different even for the same temperature interval in different countries and those behavioural differences also influences the heat load profiles. Additionally, the German tertiary sector is not necessarily representative for the entire European tertiary sector as typical working hours and production behaviour might differ throughout Europe. Furthermore, the different compositions of the industry sector in the European countries influences the heat demand profiles. Taking into account these shortcomings, which cannot be overcome in a short time-period, the German load profile is used after it is adjusted due to more important differences between the countries, such as temperature and the shares of the economic sectors within the district heat demand of the country.

Besides, the profiles are created based on the standard load profile of natural gas and they are considered as representative for the heat load in district heating. The profiles themselves were originally created for the delivery of natural gas for heating provision to non-load-metered customers. Since natural gas is mainly consumed for heat generation by end consumers, Ritter et al. [113] conclude that the profiles are as well suitable for a purified heat load forecast.

### V.B.2. Calculation of excess electricity in European countries

Excess electricity occurs when the inflexible power generation exceeds the electricity demand. Inflexible generation cannot be shut down or dispatched quickly or cost-efficiently. Renewable energy production such as wind, PV or run of river power plants are the main sources of inflexible renewable production because these depend on external factors like wind, sun or flow level of a river. This kind of generation can indeed be curtailed easily. However, these plants have very low variable costs. In addition to this, due to the policy mechanisms of some countries the RES plant operators can paid even if their plants are curtailed. Consequently, it is beneficial not to curtail them from the macroeconomic aspect. Furthermore, some other RES power plants are not dispatched market driven due to their slow response times and high feed-in tariffs.

For the calculation of excess electricity, at first, the annual generation forecasts of wind, PV and run-of-river power production are distributed to the hours of the year based on generation profiles [114] of the countries in 2015 and biomass plants are assumed to be base load. The future production of renewable energy sources is derived from the reference scenario [26]. The following figure demonstrates the expected renewable electricity production in 2030.

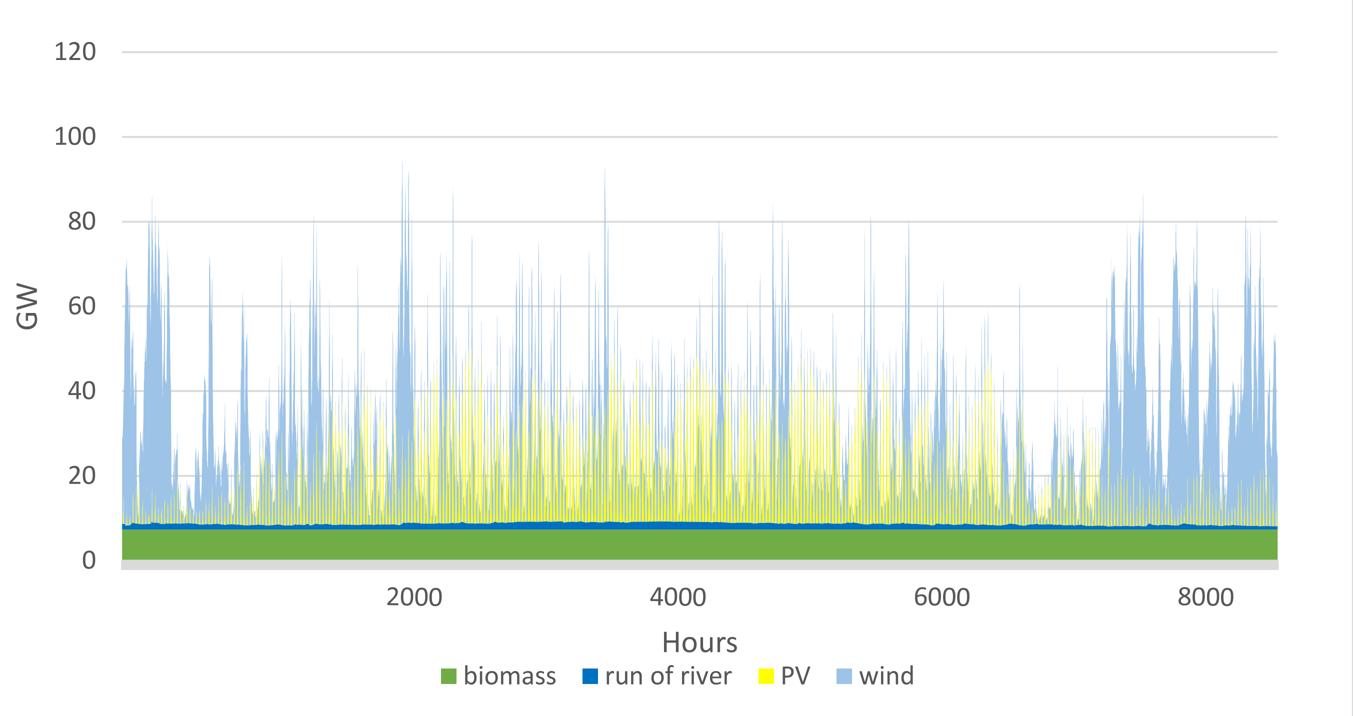


Figure 40: Inflexible RES production in Germany in 2030

Secondly, the annual demand is distributed to the hours of the year based on the 2015 demand profiles [115]. Afterwards the calculated hourly renewable production is subtracted from the hourly electricity demand. As a result, the number of negative residual load hours and the amount of excess electricity in 2030 is derived and presented in the Table 17:

Table 17: Number of hours with negative residual load and amount of excess electricity in 2030 for European countries

| Country | Number of negative residual load hours | Amount of excess electricity in GWh |
|---|---|---|
| **Austria** | 658 | 579 |
| **Denmark** | 2687 | 3886 |
| **France** | 64 | 165 |
| **Germany** | 844 | 8227 |
| **Italy** | 144 | 491 |
| **Netherlands** | 545 | 1059 |

According to this approach, the excess electricity in Austria, Denmark, France, Germany, Italy and the Netherlands sums up to 15 TWh in 2030.

One fundamental issue raised applying this approach is assuming all conventional power plants including nuclear power as flexible production. Assuming a partition of nuclear or coal power plants as inflexible base load capacity would increase the amount of excess electricity severely in some countries. This is one of the main reasons why there is not a high amount of excess electricity in France due to the approach described above.

### V.B.3. Calculation of PtH potentials through heat storages in district heating

The theoretical potential consists of the maximum amount of heat which can be absorbed in district heating. The technical potential is determined by the usable heat demand, which is very dependent to the dimensioning of the PtH/C systems. Heat storage installations together with PtH devices can help to identify the technical potential in district heating systems. These technologies bring flexibility to the electricity system; consequently, excess electricity can be converted into heat and stored in heat storage units. Installed heat storage capacities in district heating sum up to 10% to 50% of the maximum heat demand [78]. Due to the increasing need for storage capacities in the future, Prognos [78] states that 30% to 50% of highest demand in district heating is realizable as heat storage capacity which can be seen as well as the PtH potential. Several publications use this assumption and a similar approaches for calculating the technical PtH potential [21, 77, 78].

The created hourly heat demand profiles (explained in chapter V.B.1) are used to distribute the total district heat demand of the countries to the hours of the years. Total district heat demands of the countries are derived from [1]. The technical PtH potentials are calculated with the help of this distribution. Considering a thermal efficiency of 100%, the table below demonstrates the results for some European country with the assumption that 30% or 50% of highest demand in district heating is feasible as PtH potential.

Table 18: PtH potential in European countries and in whole Europe as 30% or 50% of highest peak demand

| Country | 30% of the highest demand in $GW_{el}$ | 50% of the highest demand in $GW_{el}$ |
|---|---:|---:|
| **Austria** | 2.28 | 3.80 |
| **Denmark** | 3.42 | 5.70 |
| **France** | 2.86 | 4.77 |
| **Germany** | 7.59 | 12.66 |
| **Italy** | 1.11 | 1.85 |
| **Netherlands** | 0.78 | 1.30 |

According to this approach the total technical PtH potential in district heating in Austria, Denmark, France, Germany, Italy and the Netherlands sum up to 18 to 30 $GW_{el}$.

However, our analysis(comparable to Prognos [78], Böttger et al. [21] and Götz et al. [77]) consider 30% and 50% of the maximum district heating demand as PtH potential. This assumption from [78] is not disclosed in detail. Therefore, a more restrictive analysis with the restriction that all PtH devices can only consume excess electricity is also analysed in this study to conclude about the potentials more accurately.

### V.B.4. Calculation of PtH potentials in district heating using excess electricity

The technical potential is restricted by the maximum amount of heat which can be absorbed in district heating. This technical potential can be further restricted by the amounts of excess electricity generation.

Indeed, today it is not economical for PtH devices to consume excess electricity due to high state-induced charges. These charges are also discussed in this report in detail. In the framework of the future regulations, freeing PtH devices from the state chargers in the hours with negative prices may help to incentivize the investment in the PtH plants.

Furthermore, complete excess electricity cannot be consumed only by PtH plants in district heating. The amount of excess electricity can also be larger than the simultaneous district heating demand. The technical potential calculated in this approach includes only the negative residual load when negative residual load appears simultaneously with a heat demand. If the excess electricity is larger than district heat demand in an hour, only the excess electricity load amounting to district heat demand can be covered by PtH technologies. The remaining excess electricity cannot be absorbed in district heating. A similar approach is used to calculate the technical potential in [21, 77]. The Figure 41 illustrates the simultaneous heat demand and residual electricity demand for all hours of 2030.

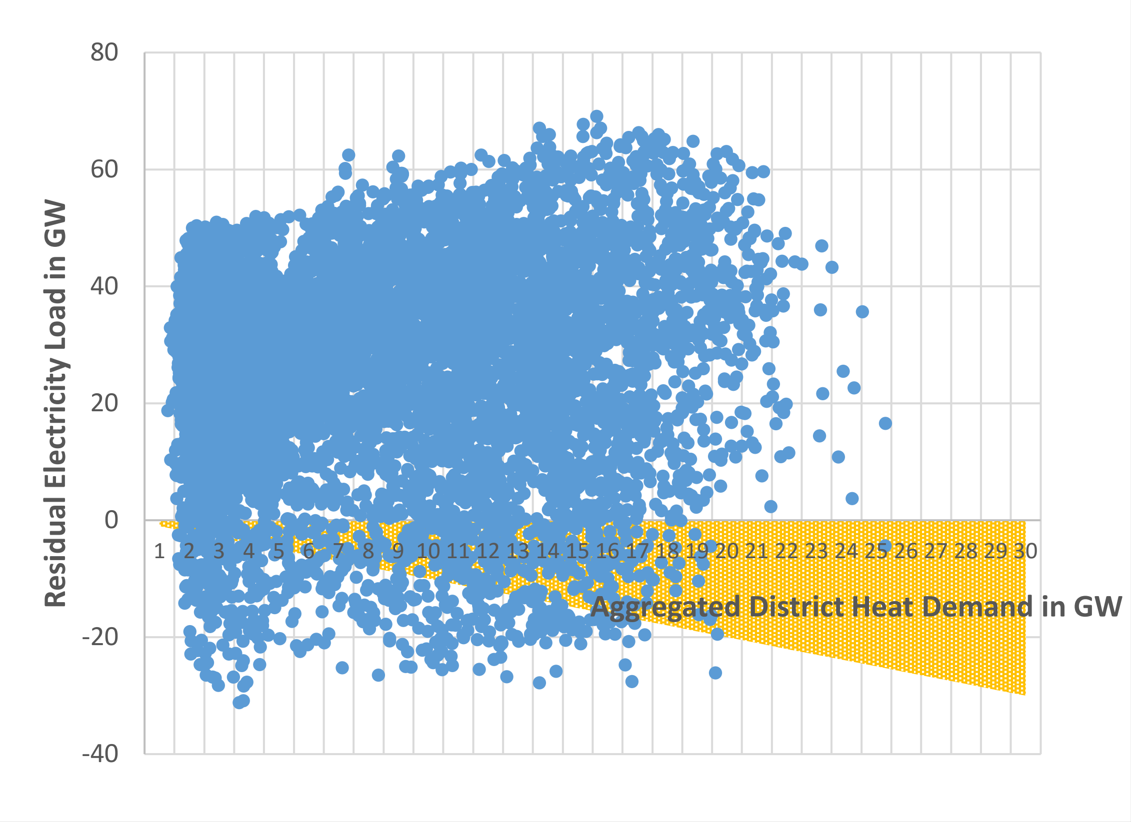


Figure 41: Heat demand and residual electricity demand in Germany in 2030 (based on own calculations)

The x-axis represents the aggregated demand in district heating and the y-axis stands for the residual load in each hour of 2030. The points representing negative residual loads above the diagonal line are the hours, in which the entire excess electricity can be absorbed by the district heating system. In other negative residual load hours only the portion of excess electricity which equals to the maximum heat demand can be absorbed. Following diagram demonstrates the number of hours and related amount of excess electricity in these hours for Germany.

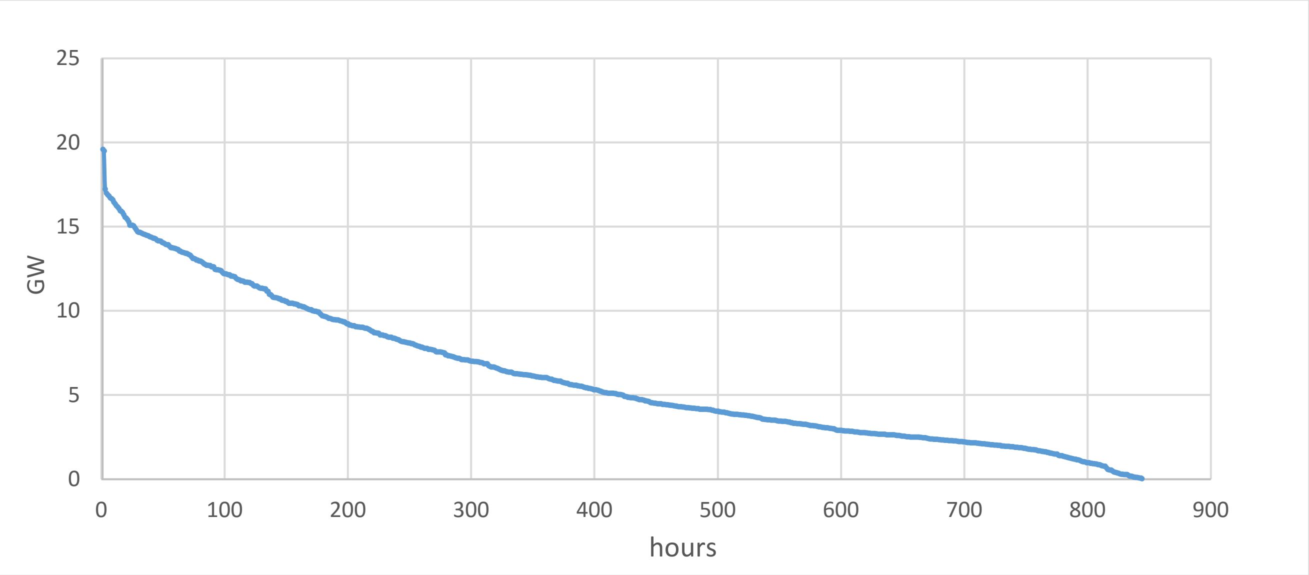


Figure 42: Excess electricity that can be technically converted to heat for district heating systems in Germany in 2030

This approach results in a PtH potential of 5176 GWh for the year 2030 in Germany which represents the area under the line demonstrated above. The same approach is applied for some other European countries. The Table 19 demonstrates the resulting PtH potentials at a thermal efficiency of 100%.

Table 19: PtH potential calculated by excess electricity that can be technically converted to heat for district heating systems in 2030

| | GWh | $GW_{el}$* |
|---|---|---|
| **Austria** | 447 | 0.89 |
| **Denmark** | 3511 | 7.02 |
| **France** | 82 | 0.16 |
| **Germany** | 5176 | 10.35 |
| **Italy** | 115 | 0.23 |
| **Netherlands** | 414 | 0.83 |

* Assuming 500 full load hours

According to this approach the total technical PtH potential in district heating, which is restricted by the amount of excess electricity in Austria, Denmark, France, Germany, Italy and the Netherlands, sum up to 10 TWh and corresponding roughly to 20 GW.

Agora Energiewende [72] states that electric boilers in Denmark are profitable with less than 500 full load hours per year. The PtH capacities demonstrated in the diagram above are calculated assuming 500 full load hours for electric boilers. These numbers are calculated by simply distributing the total excess electricity into 500 full load hours. Even though the investment of electric boilers and fixed costs of PtH devices are not so high, it is not economic to absorb the whole amount of surplus electricity. To receive an effective contribution of PtH technologies to the integration of renewable energy sources, the economic potential of the PtH plants must to be examined in detail.

Apart from that, PtH can also help to absorb the excess electricity occurring due to grid constraints. This use case also creates an important incentive for PtH investments. This potential should be addressed in future analyses.

This simplified approach has many drawbacks as explained in detail previously. Some important drawbacks are the followings. During the calculation of the district heat demand, regarding the lack of standard intraday heat profiles of different sectors, the existing standard intraday heat load profiles of Germany are assumed to be representative for the other EU countries. The temperature of the capital city is considered as the reference temperature of the respective country. The heat profiles in district heating are created based on the standard load profile of natural gas. During the calculation of the excess electricity for the year 2030, the projected annual demand and renewable production for 2030 are distributed to the hours of the year based on the 2015 profiles and the negative residual loads in a country is assumed to be excess electricity. Other framework assumptions and aspects can lead to different results.

# VI. CONCLUSIONS AND POLICY RECOMMENDATIONS

In terms of flexible production, the focus has been typically placed on conventional power generating technologies, especially hard coal (HC), combined cycle gas turbine (CCGT) and hydro, especially pumped hydro storage (PS), since so far flexibility has mainly been provided from these types of generation facilities. However, the share of electricity in total energy consumption, as well as the use of electric appliances in households is likely to increase in the coming years. This opens opportunities for demand side measures to provide flexibility.

Comparison of PtH/C with other promising demand side management options in previous chapters show that the concept of PtH/C is an effective option to match the demand and the supply strongly driven by the feed-in of renewables, especially in situations with excess electricity in the grid. Generally, heat-generating installations convert the electricity into heat, which then can be stored and used for different heat demand sinks. Coupling the electricity and the heat sector using PtH/C could be beneficial and cost-efficient for the integration of renewables into the system and for reducing the greenhouse gas emissions of the overall system. Using generated excess electricity from RES, which might otherwise be curtailed, in the heat sector also decarbonizes the heating sector and leads to an effective reduction of greenhouse gas emissions.

## VI.A. Conclusions

In the year 2012, 70% of the European H/C demand was covered by fossil fuels, whereas 12% respectively were covered by biomass and electricity. Only 8% of the final energy demand originated from district heating. The highest final energy demand, with 52%, is space heating and the lowest demand with only 5% is cooling[1]. These figures indicate that the highest potential for PtH might be in replacing conventional fuels for space heating, while the potential for PtC seems to be quite small due to the small share of cooling within final energy demand. The share of district heating might increase, due to political goals to foster this technology by the Renewable Energy [9] and the Energy Efficiency Directive [10]. Projections for the H/C demand show a slight decrease from 6497 TWh in the year 2012 to 6388 TWh in the year 2030 [1] [26]. The overall share for heating demand (space and process heating) decreases from 82% to 79% and the share for water heating demand decreases from 10% to 7%. The share in final energy demand for cooling stays constant at 5%. These figures indicate that, based on the EU Reference Scenario [26], there will be no crucial change in final energy demand for heating and cooling. However, [27] [28] and [29] include scenarios with a higher share of renewables. These scenarios project, due to a stricter $CO_2$-reduction by 2050, a decrease in the gross energy consumption as well as a decreasing heating and cooling demand by 20-30% by 2050.

The introduction of substantial amounts of intermittent RES from weather-dependent sources in several European Member States in recent years has raised a number of concerns, especially the capability of the current and future electricity power systems of providing an adequately reliable and flexible service. Demand Side Management seems to be one promising option to provide flexibility to the power system. By adding a thermal energy storage to a PtH/C system, PtH/C can provide the needed flexibility and therefore represents one of the promising DSM options, by interlinking the electricity and the heat/cool market. In general, large and small scale PtH/C with termal storage applications (TES) applications can be distinguished. Small-scale PtH/C+TES applications can be applied in the residential and commercial sectors in combination with electric heaters, heat pumps, hybrid gas/oil boilers and cooling. Large scale applications mainly focus on industrial applications, such as high voltage electrode boilers, or district heating grids, by adding an electric boiler to an existing district heating CHP plant. Adding a PtH+TES to a CHP plant further allows a decoupling of the electricity and heat production.

PtH/C applications seem to have the sufficient technical maturity and potential to play a role in future European energy markets. However, many assessments identify that the current policy framework, in particular electricity fees and tariffs, are key elements, which affect the economic feasibility of PtH/C and therefore its development. The fees and taxes which have to be paid when consuming electricity prohibit at cost-efficient use of excess electricity in the case of Germany [21]. Negative prices on the spot market are not sufficient for the economical heat production in a PtH plant [22]. Both studies point out that a reduction or a complete exemption of charges and taxes for consuming electricity can improve the economic feasibility of PtH/C.

Marketing the flexibilities of large PtH technologies via reserve energy markets is already an assessed business model in some European countries. However, the exploitation and marketing of small-scale PtH flexibilities is not yet economically viable. The economic viability of small-scale PtH technologies such as residential PtH installations is strongly influenced by the state-induced charges on electricity prices. Therefore, the future success of these business models mainly depends on the regulatory framework. In addition to this, small scale PtH applications require further technological and IT development in terms of pooling and smart controlling to be rolled out.

Traditional flexibility options are certainly the most mature and economical options, and this is the main reason why flexibility has been provided in power systems almost entirely by controlling the supply side. However, the increase in intermittent RES capacities is leading to higher flexibility needs, as i) intermittent RES increases supply side variability and uncertainty; ii) intermittent RES displaces part of the conventional generation capacity, tending to reduce the availability of flexible resources on the system.

The literature based potential analysis of PtH/C at a European level showed that the publications mainly focus on the assessment of DSR potentials in general and report PtH/C potentials in particular. However, there are only very few publications with this scope. Gils [5] identifies a load reduction potential through PtH/C of 29 $GW_{el}$ and a load increase potential of $96_{el}$ GW for the entire EU. An assessment of the IEA [67] identifies a PtH/C potential of 100 $GW_{el}$ in 2020 and of 150 $GW_{el}$ in 2030. Sia Partners [68] point out a potential capacity of 52.4 $GW_{el}$, representing roughly 10 % of the future European peak load. The assessed potentials vary between literature sources due to differing assumptions, so that further investigation seems to be necessary.

Throughout Europe, great variations regarding the different countries are identified, especially regarding heating demand and the breakdown of the sectors. The inhomogeneous nature of the European energy system, the weather conditions throughout Europe and the national regulatory frameworks make it difficult to estimate the PtH/C potential with one common approach but suggest an investigation on a national level. Therefore, a national potential assessment for Denmark, Germany, Austria, the Netherlands, France and Italy was presented and compared to gain a deeper insight for the technical and economical potentials of PtH/C and to draw conclusions for entire Europe.

In Denmark, the share of wind in the electricity production is very large. Thus, the characteristic power feed-in is strongly fluctuating and there are many hours with excess electricity – constituting favourable circumstances for PtH technologies. Some of this excess can be exported to the neighbouring countries, but the wind generation in neighbouring countries is highly correlated with the wind generation in Denmark and moreover the interconnection capacities are limited. Due to competing technologies like biomass-fired plants, the potential for electric boilers in district heating is limited and only a small increase is expected in the next years. Merely in the development of heat pumps a significant expansion is expected, replacing fossil fuel based heating boilers. However, the different publications analysed for Denmark identify an economic potential for PtH in the range of 1.6 and 3.5 $GW_{el}$ until 2030 (see Table 14).

Germany also has a large share of fluctuating feed-in from renewables. Especially in the northern part of Germany, where most of the wind capacity is installed, there is a need for flexibility in the energy system. PtH technologies are suitable for providing this flexibility and thus to integrate the renewable feed-in into the system. In the current regulatory framework, large-scale electric boilers and heat pumps are able to participate in the control energy market. For small-scale applications, high state-induced components in the electricity price are the main obstacle for economic feasibility. Several publications were analysed, identifying PtH as a key technology in the future heating sector, particularly in district heating. The presented publications mostly apply approaches from two aspects, considering both the expected excess electricity and the heating demand. All publications reveal a considerable technical PtH potential, until 2030 a potential of up to 16 $GW_{el}$ is estimated (see Table 16 for details).

In Austria, PtH is considered suitable as a supplement technology for existing CHP plants and district heating. Despite no significant market share as of today, a growing number of installations is currently put into operation. Using similar parameters as in Germany, Hinterberger [88] identifies a technical PtH potential of 2 $GW_{el}$ in 2030 for Austria.

A study by CE Delft [24] estimates the PtH potential for the Netherlands. Taking the heat demand of the residential sector, utilities and the industrial sector a technical potential of 3.1 $GW_{th}$ in summer and 6 $GW_{th}$ in winter is identified. The detailed economic analysis results in a profitable PtH potential of 2.5 $GW_{th}$ in 2023.

Another key electricity market in Europe is France, which is historically characterized by a large nuclear power share and low base load prices. As a result, rather than district heating, individual electric heating devices play a major role in the French heating sector. The temperature sensitive installed capacity amounts in total to roughly 40 $GW_{el}$. As this demand is strongly sensitive to temperature and is a key driver of the French electrical load, electricity prices are high over several days during cold periods. However, these are not necessarily favourable conditions for flexible PtH installations as the electricity demand cannot be shifted for several days but only for short periods. Nevertheless, the growing share of renewables and the future replacement of nuclear plants tend to improve the conditions for flexible PtH installations. Only two publications provide quantitative information about the French PtH potential. Gils [5] indicates a load increase potential of 16 $GW_{el}$, whereas Brouwer et al. [97] identify a technical potential for PtH/C of lower than 4 $GW_{el}$. Another national investigation was done for Italy. The results of the analysis published by Gils [5] indicate that the hourly average load increase of PtH/C applications achieves on average to 9 $GW_{el}$.

In addition to the national publications on PtH/C potentials, the entire European potential for heat pumps in the decentralized heating sector was also estimated. Flexible and controllable heat pumps are accounted to PtH as well. By analysing a publication by Ecofys prepared for EHPA [101], the 2015 market report by EHPA [102] and one publication by the Lithuanian Energy Institute [103], the future development of heat pumps in entire Europe is estimated.

The publication by Ecofys analyses three heat pump deployment scenarios in the countries Austria, Belgium, Germany, Spain, France, Italy, Sweden and the United Kingdom and assesses the financial and ecological consequences and benefits. Converted to installed capacity in the different scenarios 318 $GW_{th}$, 160 $GW_{th}$ and 114 $GW_{th}$ of heat pumps are installed respectively, whereby the first two are ambitious deployment scenarios and the latter represents a current policy implementation scenario. The study reveals no significant negative financial and a very large positive ecological impact of a more ambitious heat pump deployment.

The 2015 market report by EPHA points out a total of 7.5 million sold heat pumps since 1995, estimated to be 66.3 $GW_{th}$ of installed capacity in Europe. The largest markets are France, Sweden, Germany and Italy. In the period 2010 to 2014 the sales were relatively stable, roughly 800,000 heat pumps units with a thermal capacity of about 6.6 $GW_{th}$ were sold in Europe in 2014., A publication of the Lithuanian Energy Institute analyses the future development of the heat pump sector in Europe . When assuming a growth factor of 1.8 between 2010 and 2015 and of 1.7 between 2015 and 2020, the total thermal demand for heat pumps amounts to 140 $TWh_{th}$ in 2020. However, no underlying assumptions for these growth factors are disclosed.

Due to a lack of available studies, a new approach was developed to estimate the PtH potential in district heating throughout Europe. Two different approaches are described and the results are presented and discussed. In the first approach, based on national hourly power and heat demand data, an hourly annual heat demand profile is generated for each country. Consistent with Prognos [78], Böttger et al. [21] and Götz et al. [77], 30% and 50% respectively of the maximum district heating demand are considered as PtH potential, resulting in a total potential in the range of 18 to 30 $GW_{el}$ for the countries Austria, Denmark, France, Germany, Italy and the Netherlands. In the second approach, the (renewable) energy generation of 2030 is calculated and the number of negative residual load hours as well as the amount of excess electricity is determined. Then, the simultaneity of the hours of excess electricity and the district heating demand is checked. Thus, a PtH potential in district heating of 10 $TWh_{el}$ or roughly 20 $GW_{el}$ is determined for the countries mentioned above.

To conclude, it can be stated that PtH/C consists of many promising technology options and potential solutions for the issues raised by the current developments in the European energy system. However, to determine the exact potential of PtH/C for entire Europe is hardly possible, since many uncertain factors have to be considered and the results underlie many substantial assumptions. An estimation for entire Europe is even more difficult respecting the inhomogeneity within Europe, in terms of demand breakdowns by sector, installed heating technologies and infrastructure, weather conditions or installed renewable and conventional capacities. To foster the deployment of PtH technologies and the realization of the identified potentials, the regulatory frameworks may have to be modified on national levels, since state-induced charges or market entry barriers often pose major obstacles to PtH technologies.

In the European Union, there is so far no specific legislative regulation or directive addressing the heating and cooling sector by itself. However, it is addressed in several other Directives, as the heating sector can contribute to the achievement of the 40 % reduction of GHG-emissions goal of the European Union until 2030. The aggregation of the NREAP, which are a result of the Renewable Energy Directive, sets out a trajectory which points to a 21.4% share of renewable energies in the heating and cooling sector until 2020. That would represent an increase of nearly 10 percent points compared to 2008. The Renewable Energy Directive [9] further addresses the H/C-sector by the requirement to build infrastructure for district heating and cooling from renewable energy sources. The Energy Efficiency Directive [10] also promotes district heating and cooling and requires each European member state to assess its potential for cogeneration and district heating/cooling. Furthermore the heating sector partly overlaps with the scope of the European carbon emission trading scheme (ETS sector) and partly stands within the non-ETS sector, and therefore is also addressed in the Directive 2003/87/CE [11]. An increasing amount of power to heat and power to cooling especially in small scale installations will lead to a shift of emissions from the non-ETS sector to the ETS sector. According to the “Keep on Track” project the integration of renewable energies in the heating sector in the most European countries was on track in the year 2013. The analysis of the EEA however indicates that the recent growth rates are too small to reach the NREAP objectives.

## VI.B. Policy recommendations

The main focus of this policy report is set on the potential analyses of the PtH/C technologies, which provide flexibility to the electricity system. However, mechanisms and regulations necessary to incentivize PtH/C and related business models from practice and literature are also discussed briefly. Due to the complex structure of energy systems and markets, detailed analyses should be carried out in future studies for more concrete policy recommendations.

The heating and cooling (H/C) sector features a complex architecture of regulations that are set at different levels: European, National and Local (see chapter II.A.1). This section mainly focuses on the policy recommendations at the European level.

In light of the 2030 energy and climate targets, new policies, which consider the energy system as a whole, are being elaborated. This system-based approach allows to integrate renewable energy sources into the energy system, and to harvest efficiencies within conversion processes along the energy value chain and within industries [27] while ensuring adequacy to peak demand. In this context, PtH stands for an important source of efficiency in the conversion process of primary energy and for increasing the options for demand response in the residential [34] and industrial sector.

New forms of regulations based on a multi-technology approach are required. Thermal energy storages used for heating and cooling (H/C) should be recognised as sources of both flexibility and efficiency in the system; in particular, when used in combination with solar based district heating. Electric boilers and heat pumps should also be recognised, as new modes of flexibility and efficiency in the system at times of excess electricity generation.

As recognised in the EC’s long term strategy for heating and cooling [116], the evaluation of a specific sector policy target could be derived from the consolidation of nationally framed heating and cooling plans (% of installed capacity, contribution of heat, contribution to reduction of losses).

These long term plans should focus on the potential of renewables' resources (geothermal, solar thermal, biomass), and the specific needs of urban heating and cooling systems (as particular sources of emissions reduction) vs. rural systems.

Such policy orientation should also encourage building renovation by replacing inefficient individual heating systems (Such policies could be implemented in the Energy Efficiency Directive and/or Energy Performance Building Directive).

As part of the review of Renewables Directive, the inclusion of a heating and cooling indicative target in renewable energy policy could be considered. Another option would be to focus on specific measures like heat targeted renovation measures for the various underlying economic sectors (industry, residential), foreseen as part of the review of Energy Efficiency Directive. Finally, a Heating & Cooling technology roadmap to 2050 supporting innovation towards new technologies (trigeneration [117]) could be taken into account.

The integration of renewable energy generation in buildings is requested by Article 13 of the Renewable Energy Directive (2009/28/EU), which stipulates that by 2014 all EU Member States should consider specific minimum requirements in their building codes. This policy measure could be extended further as renovation pace is slow and does not lead to the anticipated effects [118].

Specific greenhouse gases' emissions targets for the heating and cooling sector as part of the Effort Sharing Directive need to be evaluated.

In the European electricity market, PtH/C can contribute to system balancing and ancillary services, and, therefore to energy security of supply. Case examples can be provided from the German market where PtH devices for district heating participate in the control reserve markets. However, the minimum capacity requirements for participating in balancing markets are relatively high in some countries, so that small scale PtH/C technologies cannot participate in these markets. Reducing the prequalification requirements of the balancing markets can open an additional revenue source for small scaled PtH/C projects.

A coherent framework needs to be put in place, allowing that legislation on Eco-Labelling together with electricity network codes do not contradict the reform objectives for the electricity market design. For instance, it should be ensured that new technologies (heat or cold storage) can participate in cross border schemes. It should be also ensured that Member States favour fiscal policies (e.g. taxation of heat in cogeneration) that are not detrimental to cogeneration and PtH/C.

Furthermore, regulatory adaptations are required at local level to promote innovative decentralised PtH/C systems. The share of local government's energy usage in district heating/cooling including use of excess electricity should be evaluated. The implementation of local markets can also be considered for PtH/C applications among other applications, where only excess electricity from renewable sources is marketed, that would have been otherwise curtailed. For local markets, in which the number of the actors is not sufficient, a minimum price can be introduced to avoid market distortion. However, some pilot projects are required in order to gain experience beforehand for such markets.

Based on the presented business cases and potential studies, it can be concluded that policy and financial support has a great influence on the economics of PtH/C projects. For small-scale PtH/C technologies, it is essential to establish adequate rates and regulations to capture the benefits of changes in electricity prices over time. Changes like the exemption from fees and taxes or adapted grid usage fees for system beneficial behaviour are necessary to open the market for PtH installations in the residential sector.

The analysis showed that PtH/C has the potential to play an important role in reaching the European energy and climate targets. Since PtH/C is a cross-cutting technology, the interaction between political decisions affecting the heating and cooling as well as the electricity sector should be taken into account. Implementing adequate policy measures could help to exploit the technical potential of PtH/C.

# VII. REFERENCES

[1] European Commission Directorate - general for energy, Ed., “Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment (fossil/renewables): Work package 1: Final energy consumption for the year 2012,” 2016. [Online] Available: https://ec.europa.eu/energy/sites/ener/files/documents/Report%20WP1.pdf. Accessed on: Feb. 13 2017.

[2] European Commission, “Directive 2009/31/EC: on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006,” Apr. 2009.

[3] European Commission, “Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC,” Apr. 2009.

[4] European Commission, “Directive 2009/29/EC: amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community,” Apr. 2009.

[5] H. C. Gils, “Assessment of the theoretical demand response potential in Europe,” *Energy*, vol. 67, pp. 1–18, 2014.

[6] European Commission, “Directive 2010/31/EU: on the energy performance of buildings (EPBD),” May. 2010.

[7] BMWi, “Renewable Energy Sources in Figures: National and International Development,” 2014. [Online] Available: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/renewable-energy-sources-in-figures-2014.pdf?__blob=publicationFile&v=3. Accessed on: Feb. 14 2017.

[8] *Eurostat.* [Online] Available: http://ec.europa.eu/eurostat. Accessed on: Dec. 12 2016.

[9] *Renewable Energy Directive Article 16(11)*.

[10] European Commission, “Energy Efficiency Directive (2012/27/EU) Article 14 of Directive 2012/27/EU - Repealing CHP Directive,” Oct. 2012.

[11] *Directive 2003/87/CE EU emission trading scheme (ETS) Annex 1 of the Directive - establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC*, 2003.

[12] S. Cail and M. Mistré, “Technology Note 2: ETS and markets stability reserve,” 2016.

[13] Cogen Europe, Ed., “A CHP guide to the Revised EU ETS Directive,” 139, 2011. [Online] Available: http://www.cogeneurope.eu/medialibrary/2011/04/19/0c44887c/290311%20COGEN%20Europe%20-%20A_CHP_Guide_to_EUETS.pdf. Accessed on: Feb. 14 2017.

[14] European Commission, “Directive 2010/31/EU: on the energy performance of buildings,” May. 2010.

[15] Abhishek Shivakumar et al., “Analysing RES support mechanisms in the EU post - 2020: Hot Energy Topic No. 10 - Insight_E,” Aug. 2015. [Online] Available: http://www.insightenergy.org/system/publication_files/files/000/000/018/original/HET10_Final.pdf?1447415434. Accessed on: Feb. 14 2017.

[16] Steve Pye et al., “Europe’s renewable energy policies: Too much focus on renewable electricity?: Hot Energy Topic No. 4,” Insight_E, Nov. 2014. [Online] Available:

http://www.insightenergy.org/system/publication_files/files/000/000/006/original/HET_4_Final.pdf?1438176276. Accessed on: 14.20.2017.

[17] "State of play on the sustainability of soli d and gaseous biomass used for electricity, heating and cooling in the EU: Commision Staff Working Document - SWD(2014) 259 final," Brussels, 2014.

[18] *Keep On Track - Home.* [Online] Available: http://www.keepontrack.eu/. Accessed on: Dec. 12 2016.

[19] Ulrich Fahl, "District heating in Europe: opportunities for energy savings, business and jobs - Insight_E: Rapid Response Energy Brief (RREB) No. 8," Jun. 2016. [Online] Available: http://www.stakeholderforum.org/fileadmin/files/District_heating.pdf. Accessed on: Feb. 14 2017.

[20] "Renewable Energy Policy Country Profiles," http://www.reshaping-res-policy.eu/downloads/RE-Shaping_CP_final_18JAN2012.pdf, 2011.

[21] D. Böttger, M. Götz, N. Lehr, H. Kondziella, and T. Bruckner, "Potential of the Power-to-Heat Technology in District Heating Grids in Germany," *Energy Procedia*, vol. 46, pp. 246–253, 2014.

[22] M. Götz, D. Böttger, H. Kondziella, and T. Bruckner, *Economic Potential of the "Power-to-Heat" Technology in the 50Hertz Control Area.* Accessed on: Feb. 14 2017.

[23] L. G. Ehrlich, J. Klamka, and A. Wolf, "The potential of decentralized power-to-heat as a flexibility option for the german electricity system: A microeconomic perspective," *Energy Policy*, vol. 87, pp. 417–428, 2015.

[24] S. Hers, M. Afman, S. Cherif, and Frans Rooijers, "Potential for Power-to-Heat in the Netherlands," CE Delft, Aug. 2015. [Online] Available: http://www.cedelft.eu/?go=home.downloadPub&id=1730&file=CE_Delft_3E04_Potential_for_P2H_in_Netherlands_DEF.pdf. Accessed on: Feb. 14 2017.

[25] *Energy Efficiency Trends & Policies | ODYSSEE-MURE.* [Online] Available: http://www.odyssee-mure.eu/. Accessed on: Dec. 14 2016.

[26] European Commission, Ed., "EU Energy, Transport and GHG Emissions - Trends to 2050: Reference Scenario 2013," 2013. [Online] Available: http://ec.europa.eu/transport/sites/transport/files/media/publications/doc/trends-to-2050-update-2013.pdf. Accessed on: Feb. 14 2017.

[27] European Commission, "COM(2014) 15 final: A policy framework for climate and energy in the period from 2020 up to 2030," Oct. 2012.

[28] European Commission, "Energy Efficiency Communication [COM(2014)520], Energy Efficiency Communication Impact Assessment [SWD(2014)255]," Brussels, Jul. 2014.

[29] European Commission, "Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an EU Strategy for Heating and Cooling COM(2016)51/F1 - DE," 2016.

[30] G. Majstrović, "WPP Generation Variations: Expectations and Achievements," 2012. [Online] Available: http://www.obnovljivi.com/pdf/PDF_VJETROELEKTRANE_COM/Majstrovic_MIPRO_IRP_seminar_2012.pdf. Accessed on: Feb. 14 2017.

[31] EURELECTRIC, "Linking heating and cooling with electricity. EU Heating and Cooling Strategy Consultation Forum ssue Papers," [Online] Available: http://www.eurelectric.org/media/189330/eurelectric_comments_heating__cooling_issue_papers-2015-030-0426-01-e.pdf. Accessed on: 14.20.2017.

[32] A. Ulbig and G. Andersson, “Analyzing operational flexibility of electric power systems,” *International Journal of Electrical Power & Energy Systems*, vol. 72, pp. 155–164, 2015.

[33] EDSO for smart grids, *Flexibility: The role of DSOs in tomorrow's electricity market*, 2014.

[34] P. Deane *et al.*, “Quantifying the "merit-order" effect in European electricity markets: Rapid Response Energy Brief No. 4,” INSIGHT-E.

[35] A. Arteconi, N. J. Hewitt, and F. Polonara, “State of the art of thermal storage for demand-side management,” *Applied Energy*, vol. 93, pp. 371–389, 2012.

[36] Prognos AG, Ed., “Beitrag von Wärmespeichern zur Integration erneuerbarer Energien,” Berlin, Dec. 2011. [Online] Available: https://www.prognos.com/uploads/tx_atwpubdb/111219_Prognos_Studie_AGFW_Waermespeicher_Integration_Erneuerbare_Energien_01.pdf. Accessed on: Feb. 14 2017.

[37] Galović A, “Termodinamika I,” Zagreb, 2007.

[38] Energetika marketing, Ed., “Osnove primjene dizalice topline,” Zagreb, 2009.

[39] E. Granryd, *Refrigerating Engineering*. Stocholm: Royal Institute of Technology, KTH, Department of Energy Technology, Division of Applied Thermodynamics and Refrigeration, 2005, 2003.

[40] E. Granryd, *Refrigerating Engineering: Part II*. Stocholm, 2003.

[41] M. M. Ćurko T, “Radne tvari u tehnici hlađenja R134a,” Zagreb, 2000.

[42] N. Garcia Pardo, K. Vatopoulos, A. Krook Riekola, A. Perez Lopez, and L. Olsen, *Best available technologies for the heat and cooling market in the European Union*. Luxembourg: Publications Office, 2012.

[43] European Commission Directorate - general for energy, Ed., “Mapping and analyses of the current and future (2020 - 2030) heating/cooling fuel deployment: Work package 2: Assessment of the technologies for the year 2012,” 2016. [Online] Available: https://ec.europa.eu/energy/sites/ener/files/documents/Report%20WP2.pdf. Accessed on: Feb. 13 2016.

[44] Energinet.dk, Ed., “Technology data for energy plants: Generation of Electricity and District Heating: Energy Storage and Energy Carrier Generation and Conversion,” 2012.

[45] L. F. Cabeza, Ed., *Advances in thermal energy storage systems: Methods and applications*. Oxford u.a.: Woodhead Publ, 2015.

[46] A. Castell and C. Solé, “An overview on design methodologies for liquid–solid PCM storage systems,” *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 289–307, 2015.

[47] *Energy price statistics - Statistics Explained.* [Online] Available: http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics. Accessed on: Feb. 14 2017.

[48] EURELECTRIC, Ed., “Flexible generation: Backing up renewable,” 2011. [Online] Available: http://www.eurelectric.org/media/61388/flexibility_report_final-2011-102-0003-01-e.pdf. Accessed on: Feb. 07 2017.

[49] J. Hentschel, U. Babić, and H. Spliethoff, “A parametric approach for the valuation of power plant flexibility options,” *Energy Reports*, vol. 2, pp. 40–47, 2016.

[50] T. Plavšić, “Technologies of smart energy systems,” 2015.

[51] Mihajlo Firak, “New technologies in Energetics,” 2012.

[52] ENEA Consulting, Ed., “The potential of power-to-gas,” 2016. [Online] Available: 13.02.2017. Accessed on: http://www.enea-consulting.com/wp-content/uploads/2016/01/ENEA-Consulting-The-potential-of-power-to-gas.pdf.

[53] Ecofys, “Flexibility options in electricity systems,” 2014. [Online] Available: http://www.ecofys.com/files/files/ecofys-eci-2014-flexibility-options-in-electricity-systems.pdf. Accessed on: Feb. 14 2017.

[54] *NERA & AEA cost source.* [Online] Available: http://2050-calculator-tool-wiki.decc.gov.uk/cost_sources/61. Accessed on: Dec. 07 2016.

[55] I. Drmač, D. Jakšić, and N. Karadža, "Exploring the strengths and weaknesses of European innovation capacity within the Strategic Energy Technologies (SET) Plan: Policy Report 3,” 2015.

[56] A. Shivakuma, P. Dean, N. Bo, and A. Faure, “Business models for flexible production and storage: Policy Report 4,” vol. 2015.

[57] *Enerstorage - Power to Heat Contracting - Power to Heat. Industrial Scale.* [Online] Available: http://enerstorage.de/. Accessed on: Dec. 07 2016.

[58] Technische Werke Ludwigshafen AG (TWL), *Technische Werke Ludwigshafen AG (TWL) - TWL-Wachstumsprojekte: Power-to-Heat-Anlage und Wärmespeicher am Netz.* [Online] Available: http://www.twl.de/de/Unternehmen/Newsroom/Pressemeldungen/Pressearchiv1/Pressemitteilungen/TWL-Wachstumsprojekte-Power-to-Heat-Anlage-und-Waermespeicher-am-Netz_393725.html. Accessed on: Dec. 07 2016.

[59] ENBW, Ed., “Ergebnisbericht Modellversuch „Flexibler Wärmestrom“,” Karlsruhe, 2015. [Online] Available: https://www.haw-hamburg.de/fileadmin/user_upload/Forschung/CC4E/Newsletter/Content/BK_ergebnisbericht-modellversuch_final.pdf. Accessed on: Feb. 14 2017.

[60] *From wind power to heat pumps.* [Online] Available: http://www.energinet.dk/EN/FORSKNING/Energinet-dks-forskning-og-udvikling/Sider/Fra-vindkraft-til-varmepumper.aspx. Accessed on: Dec. 07 2016.

[61] *IT infrastructure for distributed energy ressources.* [Online] Available: https://insero.com/en/current-projects/sdvp/. Accessed on: Dec. 07 2016.

[62] International Energy Agency, Ed., “Linking Heat and Electricity Systems: Co-generation and District Heating and Cooling Solutions for a Clean Energy Future,” 2014.

[63] European Commission, “Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Official Journal of the European Union. 55.,” 2012.

[64] Cherrelle Eid, “Demand Response in Europe’s Electricity Sector: Market barriers and outstanding issues,” [Online] Available: https://www.ifri.org/sites/default/files/atoms/files/actuelle_demand_response_7_aprilvf_aurelie.pdf. Accessed on: Feb. 14 2017.

[65] Smart Energy Demand Coalition (SEDC), Ed., “Mapping Demand Response in Europe Today. Smart Energy Demand Coalition,” 2015.

[66] International Energy Agency, “World Energy Outlook 2016,” 2016. [Online] Available: https://www.iea.org/media/publications/weo/WEO2016Chapter1.pdf. Accessed on: Feb. 14 2017.

[67] International Energy Agency, Ed., “Energy Technology Perspective: Towards sustainable energy systems,” 2016.

[68] Sia Partners, Ed., “Demand response: a study of its potential in Europe: Insight energy & environment,” 2014.

[69] ENTSO-E, Ed., “Scenario Outlook & Adequacy Forecast 2015,” Jun. 2015.

[70] J. Bertsch, C. Growitsch, S. Lorenczik, and S. Nagl, "Flexibility options in European electricity markets in high RES-E scenarios: Study on behalf of the International Energy Agency (IEA) - Final Report ,," Energiewirtschaftliches Institut, Oct. 2012. [Online] Available: http://www.ewi.uni-koeln.de/fileadmin/user_upload/Publikationen/Studien/Politik_und_Gesellschaft/2012/Flexibility_options_in_the_European_electricity_markets.pdf. Accessed on: Feb. 14 2017.

[71] Ecofys, "Impacts of restricted transmission grid expansion in a 2030 perspective in Germany: Final report," Aug. 2013. [Online] Available: http://www.ecofys.com/files/files/ecofys-2013-impact-grid-expansion-2030.pdf. Accessed on: Feb. 14 2017.

[72] Agora Energiewende, "The Danish Experience with Integrating Variable Renewable Energy," Sep. 2015. [Online] Available: https://www.agora-energiewende.de/fileadmin/Projekte/2015/integration-variabler-erneuerbarer-energien-daenemark/Agora_082_Deutsch-Daen_Dialog_final_WEB.pdf. Accessed on: Feb. 14 2017.

[73] P. Sorknæs, H. Mæng, T. Weiss, and A. N. Andersen, "Facilitating energy storage to allow high penetration of intermittent renewable energy: Overview of current status and future development scenarios of the electricity system in Denmark – allowing integration of large quantities of wind power," Jul. 2013.

[74] K. Hedegaard and M. Münster, "Influence of individual heat pumps on wind power integration – Energy system investments and operation," *Energy Conversion and Management*, vol. 75, pp. 673–684, 2013.

[75] A. G. Energiebilanzen eV, "Bruttostromerzeugung in Deutschland ab 1990 nach Energieträgern," Oct. 2016. [Online] Available: http://www.ag-energiebilanzen.de/. Accessed on: Feb. 13 2017.

[76] Bundesnetzagentur, "3. Quartalsbericht zu Netz-und Systemsicherheitsmaßnahmen Viertes Quartal sowie Gesamtjahresbetrachtung 2015," Aug. 2016. Accessed on: Oct. 31 2016.

[77] M. Götz, D. Böttger, H. Kondziella, and T. Bruckner, *Economic Potential of the "Power-to-Heat" Technology in the 50Hertz Control Area.* Accessed on: Feb. 14 2017.

[78] Prognos AG, Ed., "Beitrag von Wärmespeichern zur Integration erneuerbarer Energien," Berlin, Dec. 2011. [Online] Available: https://www.prognos.com/uploads/tx_atwpubdb/111219_Prognos_Studie_AGFW_Waermespeicher_Integration_Erneuerbare_Energien_01.pdf. Accessed on: Feb. 14 2017.

[79] D. Böttger, M. Götz, M. Theofilidi, and T. Bruckner, "Control power provision with power-to-heat plants in systems with high shares of renewable energy sources – An illustrative analysis for Germany based on the use of electric boilers in district heating grids," *Energy*, vol. 82, pp. 157–167, 2015.

[80] C. Pellinger and T. Schmid, "Verbundforschungsvorhaben Merit Order der Energiespeicherung im Jahr 2030," Forschungsstelle für Energiewirtschaft e.V., 2016. [Online] Available: https://www.ffe.de/images/stories/Themen/414_MOS/20160531_MOS_Hauptbericht.pdf. Accessed on: Feb. 14 2017.

[81] Agora Energiewende, Ed., "Power-to-Heat zur Integration von ansonsten abgeregeltem Strom aus Erneuerbaren Energien: Handlungsvorschläge basierend auf einer Analyse von Potenzialen und energiewirtschaftlichen Effekten," Jun. 2014.

[82] E-Control, Ed., "Stromkennzeichnungsbericht 2016," 2016. [Online] Available: https://www.e-control.at/documents/20903/388512/EC_Stromkennzb15_NEU.pdf. Accessed on: Nov. 21 2016.

[83] VSE, BDEW, and Österreichs E-Wirtschaft, Eds., "Energie-Initiative der Alpenländer: D-A-CH Deutschland Österreich Schweiz," Mar. 2013.

[84] Fachverband Gas Wärme (FGW), “Zahlenspiegel 2016: Erdgas und Fernwärme in Österreich,” Vienna, Sep. 2016. [Online] Available: http://www.gaswaerme.at/media/medialibrary/2016/09/zahlenspiegel_2016.pdf. Accessed on: Feb. 14 2017.

[85] Statistik Austria, *Energiebilanzen.* Accessed on: Feb. 14 2017.

[86] *Salzburg AG nimmt zweite Power-to-Heat-Anlage in Betrieb - Presse - Salzburg AG für Energie, Verkehr & Telekommunikation.* [Online] Available: https://www.salzburg-ag.at/presse/pressearchiv/salzburg-ag-nimmt-zweite-power-to-heat-anlage-in-betrieb-2942/. Accessed on: Feb. 14 2017.

[87] *Hall AG - Tirols erste „Power-To-Heat-Anlage“ wird in Hall i. T. Realität.* [Online] Available: http://www.hall.ag/Media-Presse/Archiv-2015/Tirols-erste-Power-To-Heat-Anlage-wird-in-Hall-i.-T.-Realitaet?%2FNews%2FTirols-erste-Power-To-Heat-Anlage-wird-in-Hall-i.-T.-Realitaet. Accessed on: Feb. 14 2017.

[88] R. Hinterberger, “Flexibilitäten zwischen Strom und Wärme: Optimierung von Wärmesystemen im Kontext von Hybridnetzen,” Wien, Berichte aus Energie- und Umweltforschung 21/2015, Sep. 2014.

[89] ENTSO-E, “System Outlook & Adequacy Forecast 2015-2030,” Brussels, Jun. 2015.

[90] Réseau de transport d'électricité (RTE), “Annual Electricity Report 2015,” 2016.

[91] Eurostat, *Electricity prices for households and industry 2013-2015.* [Online] Available: http://ec.europa.eu/eurostat/data/database. Accessed on: Nov. 15 2016.

[92] C. A. Programme, *France approves historic energy transition bill.* [Online] Available: http://www.climateactionprogramme.org/news/france_approves_historic_energy_transition_bill. Accessed on: Nov. 30 2016.

[93] D. Scamman and M. Newborough, “Using surplus nuclear power for hydrogen mobility and power-to-gas in France,” *International Journal of Hydrogen Energy*, vol. 41, no. 24, pp. 10080–10089, 2016.

[94] Réseau de transport d'électricité (RTE), “French Capacity Market: Report accompanying the draft rules,” 2014.

[95] Réseau de transport d'électricité (RTE), “Bilan Électrique 2012,” 2013.

[96] Smart Energy Demand Coalition (SEDC), Ed., “Mapping Demand Response in Europe Today: Tracking Compliance with Article 15.8 of the Energy Efficiency Directive. Smart Energy Demand Coalition,” Apr. 2014.

[97] A. S. Brouwer, M. van den Broek, W. Zappa, W. C. Turkenburg, and A. Faaij, “Least-cost options for integrating intermittent renewables in low-carbon power systems,” *Applied Energy*, vol. 161, pp. 48–74, 2016.

[98] Terna, *Dati statistici sull’energia elettrica in Italia – 2015. Nota di sintesi.* [Online] Available: http://download.terna.it/terna/0000/0841/77.PDF. Accessed on: Dec. 28 2016.

[99] Terna, *Dati storici.* [Online] Available: http://download.terna.it/terna/0000/0837/47.PDF. Accessed on: Dec. 28 2016.

[100] *Deloitte, 2015.European energy market reform. Country profile: Italy.* [Online] Available: https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Energy-and-Resources/gx-er-market-reform-italy.pdf. Accessed on: Dec. 28 2016.

[101] Ecofys, *Heat Pump Implementation Scenarios until 2030*.

[102] EHPA, *Heat Pump Market and Statistics Report 2015: Executive Summary.* [Online] Available: http://www.ehpa.org/fileadmin/red/07._Market_Data/2014/EHPA_European_Heat_Pump_Market_and_Statistics_Report_2015_-_executive_Summary.pdf.

[103] V. Gaigalis, R. Skema, K. Marcinauskas, and I. Korsakiene, “A review on Heat Pumps implementation in Lithuania in compliance with the National Energy Strategy and EU policy,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 841–858, 2016.

[104] T. Boßmann *et al.,* “Appropriate policy portfolios for (nearly) mature RES-E technologies: D 3.2.1. A report compiled within the European IEE project towards2030-dialogue,” Apr. 2016.

[105] Greenpeace, Ed., “powE[R] 2030: A European grid for 3/4 renewable electricity by 2030,” 2014. [Online] Available: https://www.greenpeace.de/files/publications/201402-power-grid-report.pdf. Accessed on: Feb. 13 2017.

[106] M. Steurer, U. Fahl, A. Voß, and P. Deane, *Curtailment: an option for cost-efficient integration of variable renewable generation?: INSIGHT-E Hot Energy Topic.* [Online] Available: http://www.insightenergy.org/ckeditor_assets/attachments/36/het2.pdf.

[107] B. Pfluger, F. Sensfuß, G. Schubert, and J. Leisentritt, “Tangible ways towards climate protection in the European Union: (EU Long-term scenarios 2050),”

[108] Agora Energiewende, “The European Power System in 2030: Flexibility Challenges and Integration Benefits,” Jun. 2015. [Online] Available: https://www.agora-energiewende.de/fileadmin/Projekte/2014/Ein-flexibler-Strommarkt-2030/Agora_European_Flexibility_Challenges_Integration_Benefits_WEB_Rev1.pdf. Accessed on: Feb. 14 2017.

[109] T. Slot and P. van der Wijk, “Extended Flexibility Study: Power to gas potential from curtailment in 2025 and 2030,” 2014.

[110] S. Collins, J. P. Deane, and B. P. Ó. Gallachóir, “The EU Power System in 2030: Investigating Electricity Sector Challenges Proc,” Abu Dhabi, Jun. 2015.

[111] Bundesverband der deutschen Gas- und Wasserwirtschaft (BGW), Ed., “Abwicklung von Standardlastprofilen: Praxisinformation P 2007/13 Gastransport/Betriebswirtschaft,” Berlin, 2017.

[112] *Weather Forecast & Reports - Long Range & Local | Wunderground | Weather Underground.* [Online] Available: https://www.wunderground.com/. Accessed on: Nov. 23 2016.

[113] P. Ritter, L. Nicklaus, and D. Filzek, “Wärmelastprognose: Ergebnisbericht,” 2012. [Online] Available: http://www.regmodharz.de/fileadmin/user_upload/bilder/Service/Arbeitspakete/AP-Bericht_Waermelastprognose_AP2.4_CUBE.pdf. Accessed on: Nov. 23 2016.

[114] *ENTSO-E Transparency Platform.* [Online] Available: https://transparency.entsoe.eu/. Accessed on: Dec. 05 2016.

[115] *European Network of Transmission System Operators for Electricity.* [Online] Available: https://www.entsoe.eu/. Accessed on: Nov. 29 2016.

[116] European Commission, “EU Strategy for Heating and Cooling: COM(2016) 51 final,” Brussels, Feb. 2016.

[117] M. Jradi and S. Riffat, “Tri-generation systems: Energy policies, prime movers, cooling technologies, configurations and operation strategies,” *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 396–415, 2014.

[118] Entranze consortium, *Laying down the pathways to nearly zero-energy buildings: A toolkit for policy makers.* [Online] Available: http://www.entranze.eu/files/downloads/D6_11/entranze_report_final.pdf. Accessed on: Dec. 12 2016.