# METIS Studies

## Study S6

*Decentralised heat pumps: system benefits under different technical configurations*

*METIS Studies*
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# 1. ABBREVIATIONS AND DEFINITIONS

## 1.1. ABBREVIATIONS

| Abbreviation | Definition |
|---|---|
| ASHP | Air-source heat pump |
| CAPEX | Capital expenditures |
| CCGT | Combined-cycle gas turbine |
| COP | Coefficient of performance |
| el | electric |
| EU28 | The 28 Member States of the European Union, including UK |
| EU28+6 | European countries modelled in METIS power system module (EU28 + Bosnia and Herzegovina, FYR of Macedonia, Montenegro, Norway, Serbia, Switzerland) |
| HP | Heat pump |
| OCGT | Open-cycle gas turbine |
| OPEX | Operational expenditures |
| PHS | Pumped hydro storage |
| RES | Renewable energy source |
| th | thermal |
| vRES | Variable renewable energy source |
| y | Year |

## 1.2. METIS CONFIGURATION

*Table 1 - METIS configuration*

| METIS configuration | |
|---|---|
| **Version** | METIS v1.3 |
| **Modules** | Power system module + demand module |
| **Scenarios** | METIS REF16-2030, EuCo30-2050 |
| **Time resolution** | Hourly (8760 consecutive time-steps per year) |
| **Spatial granularity** | Member State |
| **Weather realisations** | Test case 37 (year 2001) |

# 2. EXECUTIVE SUMMARY

Space heating represents a major part of households and commercial buildings' energy consumption, with around 70% of the whole final energy consumption. This heating demand is currently mainly covered by conventional boilers, fuelled by fossil energies such as gas, oil or coal. In a context of an increasing penetration of renewable energy sources in the European power mix, using electricity to generate heat could play an important role in the decarbonisation of the space heating sector, and thereby contribute to meet the European 2030 and 2050 targets for greenhouse gas emission reduction.

The most commonly known power-to-heat technology is the electric radiator, with an energy conversion efficiency close to 100%. However, the most efficient way to produce heat with power is the use of heat pump systems, where a large part of the produced heat is extracted from an external heat source (e.g. the ambient air). The overall efficiency (i.e. electricity-to-heat conversion factor) of such systems is currently around 3 to 4, and can reach up to 5 for state-of-the-art ground source heat pumps. Heat pumps are often combined with a back-up heater to avoid over-dimensioning and complement heat supply during the coldest days.

The objective of this study is to evaluate the system benefits of decentralised heat pumps in the EU under different technical configurations. A literature review is first realised in order to gather technical information about various power-to-heat technologies and more specifically about technical and economic parameters of heat pumps. Subsequently, different options are defined (1) to assess the benefits of heat pumps over conventional boilers, (2) to estimate the flexibility offered by heat pumps coupled with thermal storage, and (3) to analyse the profitability of heat pumps with gas back-up heaters. These different options are analysed for two different EU power system scenarios: a 2030 "business-as-usual" scenario and a further decarbonised 2050 scenario, with a renewables share of 65% in power production and a high $CO_2$ price.

The analysis is realised with the EU power system model METIS. METIS simulates the hourly dispatch of all generation, storage and interconnection capacities, taking into account the capacity mix and demand of all individual EU Members States. Specific effort is dedicated in this study to the extension of the METIS tool in order to model adequately the hourly functioning of heat pumps under varying temperature profiles and to capture the heat production of heat pumps coupled with an electric or gas back-up heater.

This study reveals that heat pumps represent an efficient way to decarbonise the heating sector. This effect is all the more pronounced with a lower carbon content in the electricity mix. However, in the 2030 business-as-usual scenario, the profitability of mono-energetic heat pumps is more than uncertain, due to significant investment costs related to the installation of heat pumps and to the need for additional peak power generation to meet the increased load peaks. In the 2050 scenario in turn, the high $CO_2$ price makes that the monetary savings from avoided $CO_2$ emissions from gas boilers offset the required additional investments, thus leading to the profitability of heat pumps from a system point of view.

Both scenarios take advantage of the flexibility offered by heat pumps with thermal storage, in association with real-time pricing. The production of low-carbon power generation units featuring low variable generation costs is increased, curtailment of renewable power generation is reduced, and the power generation costs are lowered.

Ultimately, equipping heat pumps with gas instead of electric back-up heaters appears to be a promising compromise to curb the potential increase in electricity demand peaks, and thus the required investments in additional peak power units. The reduction in investment costs makes the shift towards heat pumps becoming profitable under the 2030 business-as-usual scenario, but at the expense of a slight decrease in the heat pumps' $CO_2$ emission reduction potential.

# 3. INTRODUCTION AND BACKGROUND

## 3.1. INTRODUCTION

At the EU level, buildings account for 36% of $CO_2$ emissions and 40% of energy consumption (European Commission, 2018), covering the households (26%) and the services sector (14%). That is, buildings' energy consumption exceeds the consumption for the transport (33%) and the industry sector (25%).

Space heating represents a major part of households' energy consumption (cf. Figure 1), with about 70% of the whole final energy consumption in 2015. About 65% of the whole final energy consumption for residential space heating is covered by fossil energies, mainly by natural gas but oil and coal still represent an important part (gas 43%, oil 17%, coal 5%). In commercial buildings, the situation is very similar.

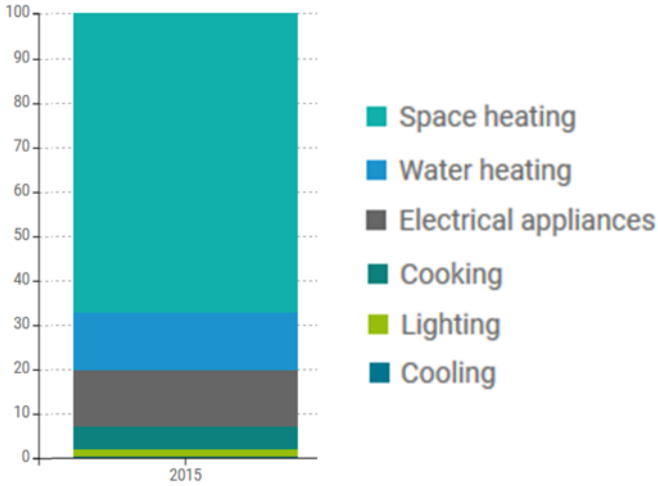


*Figure 1 - Household energy consumption in the EU[1], in %*

In order to reduce greenhouse gas emissions by 80% to 95% until 2050 (compared to the year 1990), the EU has set interim targets for the year 2030 which were updated in June 2018. They include (European Commission, 2018):

- A 40% cut in $CO_2$ emissions compared to 1990;
- A share of at least 32% share of renewable energy in energy consumption;
- A reduction of energy demand by 32.5% compared to the 2007 baseline.

Over the last few years, the cost of electric renewable technologies has dropped substantially, especially for wind and solar technologies. Power generation from renewable sources is currently seen as one of the main pillars for the decarbonisation of the EU energy system.

With a greener power mix, so-called power-to-heat technologies (i.e. the use of electricity to generate heat) could have an important role in the decarbonisation of the space heating sector. The simplest appliance is the electric radiator, with an energy conversion efficiency of close to 100%. However, the most efficient way to produce heat with power is to use heat pump systems, where a large part of the produced heat is extracted from an external heat source (e.g. the ambient air). With these systems, the whole efficiency is currently around 3-4, and can reach up to 5 for state-of-the-art ground source heat pumps. That is, one unit of electricity generates three to five units of heat.

At the same time, the stochastic availability of the natural resources for solar and wind power implies that renewable power production is variable over time and non-dispatchable.

[1] Energy Efficiency Trends & Policies, ODYSSEE-MURE project

Thus, a rising share in electricity generation from variable renewables will have substantial impacts on the future electricity system. To accommodate the variable production, adequate flexibility technologies are required, in order to counterbalance this variability and to keep supply and demand balanced at any time. In this context, flexible power-to-heat technologies could be a way to integrate this variable production, especially when combined with thermal storage.

### 3.2. OBJECTIVES OF THE STUDY

The main objective of the study is to analyse how power-to-heat technologies, and especially decentralised heat pumps, could help to decarbonise the EU energy system. Given the relevance of space heating end-use in residential and tertiary energy demand, this study focuses in particular on these two sectors.

A review of current power-to-heat technologies was first performed to have a better grasp of their main characteristics, and to assess the flexibility offered by each technology. Different *options* were then created to evaluate how different configurations of heat pump systems could contribute to the decarbonisation of the EU energy system. These options were designed in order to answer three major questions:

- Replacing gas boiler by electric heat pumps appears to be a virtuous way to decarbonise the heating sector, but at what cost?
- How could heat pumps with thermal storage and smart metering increase electricity system flexibility?
- Could bivalent heat pumps equipped with a gas backup heater be a solution to take advantage of high heat pumps' efficiency, while limiting costs?

In order to adequately reply to the previous questions, another objective of the study consisted of the development of additional functionalities of the METIS software, enabling a detailed representation of power demand. A decomposition of the power demand was realised to allow for an explicit simulation of hourly electricity demand of heat pumps with particular attention to adequately capture thermo-sensitivity and variation throughout the year.

A literature review is first realised in order to gather information about various power-to-heat technologies and more specifically about the technical and economic parameters of heat pumps (cf. Section 4). Subsequently, different options of heat pump configuration are defined in order to answer the three major questions previously introduced. These different options are analysed for two different EU power system scenarios: a 2030 "business-as-usual" scenario and a further decarbonised 2050 scenario, with a renewables share of 65% in power production and a high $CO_2$ price. The different options and the two scenarios are defined in Section 5.

Finally, Sections 6 to 8 gather the analyses of the different options, one section dedicated to each question. The study's general conclusions are outlined in Section 9.

### 3.3. THE METIS MODEL

METIS is an on-going project[2] initiated by the European Commission's DG Energy for the development of an energy modelling software, with the aim to further support DG Energy's evidence-based policy making, especially in the areas of electricity and gas. The model is developed by a consortium (Artelys, IAEW, ConGas, Frontier Economics), which already

[2] See http://ec.europa.eu/dgs/energy/tenders/doc/2014/2014s_152_272370_specifications.pdf

delivered a version of METIS covering the power system, power markets, and gas system modules[3].

METIS is an energy modelling software covering in high granularity (in time and technological detail, as well as representing each Member State of the EU and relevant neighbouring countries) the whole European power system and markets. METIS relies on the Artelys Crystal Super Grid platform. This platform provides a graphical user interface (cf. Figure 2), optimisation services and scripting capabilities that allow the user to extend the software according to his individual needs.

*Figure 2 - Snapshot of METIS' graphical user interface, highlighting the distinction of Member States*

METIS includes its own modelling assumptions, datasets and comes with a set of pre-configured scenarios. These scenarios usually rely on the inputs and results from the European Commission's projections of the energy system, for instance with respect to the capacity mix or annual demand. Based on this information, METIS allows to perform the hourly dispatch simulation (for the length of an entire year, i.e. 8760 consecutive time-steps per year). The result consists of the hourly utilisation of all national generation, storage and cross-border capacities as well as demand side response facilities.

The uncertainties regarding the demand and renewable power generation dynamics are captured thanks to a set of 50 weather scenarios taking the form of hourly time-series of wind, irradiance and temperature, which influence demand (through a thermal gradient), as well as PV and wind generation.

[3] More information can be found on the METIS webpage : https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis

# 4. Overview of the main power-to-heat technologies, with a special focus on heat pumps

A literature review on the power-to-heat sector provides information about the characteristics of the main electric heating technologies applied in the EU's buildings sector. This includes the analysis of the potential flexibility offered by power-to-heat technologies integrated in smart grids to the power system. Since the model-based analysis of this study focusses on decentralised heat pump systems, special attention is paid to the modelling of heat pump within the METIS tool.

## 4.1. Literature review on power-to-heat technologies, and the associated flexibility

For space heating in the residential and tertiary sectors, different heating technologies are available. Currently, a large part of the required heat is produced with boilers fuelled by fossil fuels (i.e. gas, oil and coal), cf. Figure 3. Gas is mainly used in places where an associated network exists (typically in urban areas), while oil, coal and biomass are more commonly used in less densely populated areas.

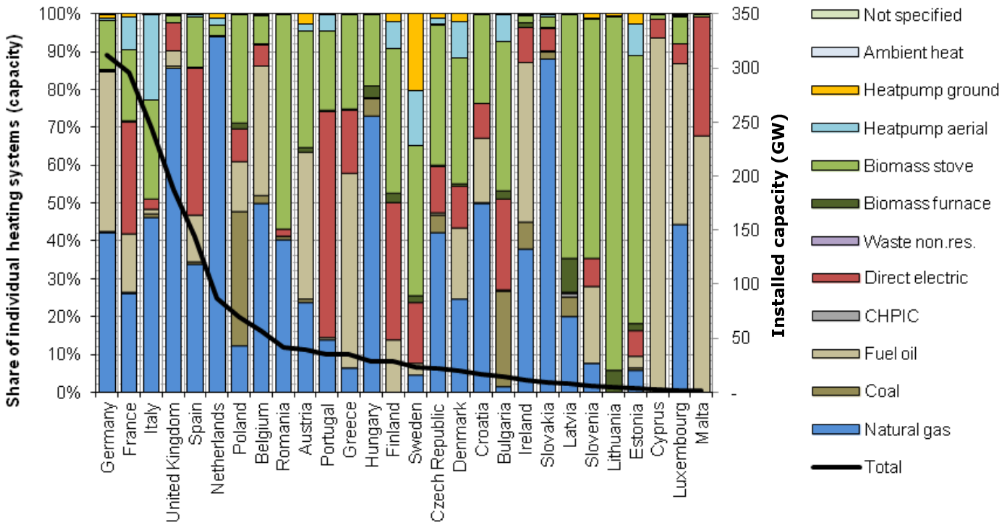


*Figure 3 – Current share of heating technologies and total installed capacity by country, excluding district heating (EU-28) (Fleiter, Steinbach, & Ragwitz, 2016)*

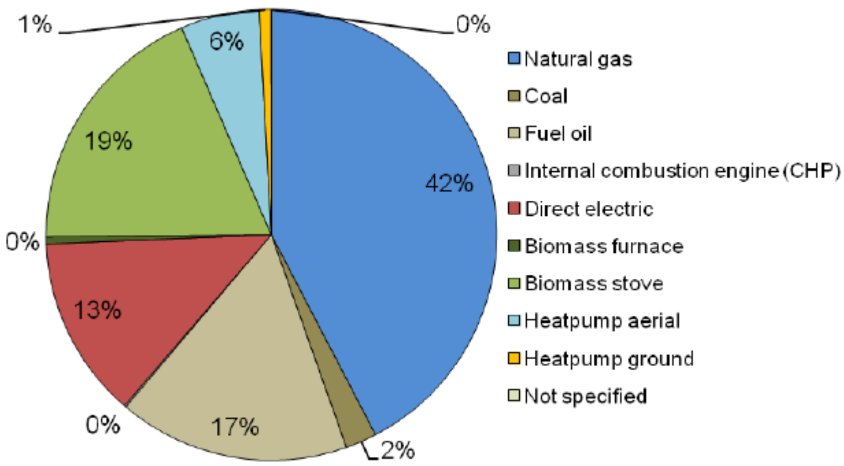


*Figure 4 - Installed heating capacity in buildings in EU-28 (Fleiter, Steinbach, & Ragwitz, 2016)*

Power-to-heat technologies do not represent the most widespread systems to produce heat, since electricity is currently more expensive than the fossil alternatives. Nonetheless, in selected countries like France, Spain or Portugal, direct electric heating covers an important share. Heat pumps have so far disseminated in particular in Sweden, Italy, France and other Baltic and Scandinavian countries. However, with a growing share of renewable energies in the European power mix, an electrification of the heat sector could also foster its decarbonisation.

A literature review was conducted to collect information about the different power-to-heat technologies, in order to assess their main characteristics (cf. Section 4.1.1). In a future with a growing share of variable and non-controllable renewable power sources, adequate flexibility technologies would be required to balance the production with the demand at any time. Associated with thermal storage and smart metering, power-to-heat technologies could contribute to meet these flexibility needs. Section 4.1.2 addresses the characteristics of the potential flexibility supply through heat pumps and the associated limitations. Section 4.1.3 lists investment cost assumptions related to the analyses carried out in this study.

### 4.1.1. ***POWER-TO-HEAT TECHNOLOGY REVIEW***

Heat for space-heating can be produced through centralised or decentralised power-to-heat installations. In centralised units, the electricity is converted into heat in large facilities physically separate from the consumption sites. The produced heat is transported to the buildings via a heating network. In contrast, in the decentralised case, the heat is produced directly inside the building where the heat is consumed. The heating equipment can either be located in the house/apartment, or shared between different apartments in the same buildings (also referred to as *community heating*). It is important to note that the limit between district heating and community heating can be blurred, since a large complex of several buildings with a common heating system is at the limit of the two approaches.

Decentralised and centralised heating installations are similar with respect to their technical configuration and the way to produce heat, but they differ in size and working behaviour. The following overview focusses on decentralised power-to-heat equipment.[4]

**Electric radiators/convectors**

Electric radiators represent the most widespread power-to-heat technology. The heat is produced by an electric resistance that can either heat directly the air inside a room (via convectors) or a buffer material (such as steel, aluminium or cast iron) which is in turn releasing the heat up the surrounding air (radiators).

Typically, each room of the building/house is equipped with an electric radiator, and the desired room temperature can be controlled by a regulator. Current radiators often offer advanced ways to control the temperature, with programmable heating hours, remote-controlled starting times, etc.

Radiators feature relatively low investment costs compared to other heating technologies, but have high operational costs because of the elevated electricity price level compared to other energies. They are often installed in warm countries where space heating is limited (e.g. Malta, Portugal or Spain) or in countries with abundant and low-cost electricity, coming from nuclear or hydroelectricity (e.g. France or Finland).

**Electric boilers**

Instead of heating the ambient air, it is also possible to use electricity to heat water which is then distributed via a central heating system to heat a building. An electric resistance is installed inside a water tank (functioning as heat buffer), producing heat which is then transported to each room via a water-borne heating system.

[4] See METIS study S9 for further information about centralised power-to-heat applications being incorporated in district heating systems and the related energy system impacts.

Electric boilers have a simple design, are easy to operate, and provide a comfortable heat thanks to the radiative central heating system.

Electric boilers suffer from the same drawbacks than electric radiators, that is high operational costs. In addition, they exhibit higher investment costs related to the necessary installation of the central water-borne heating system.

**Heat pumps**

Heat pumps are devices that extract heat from an external heat source (typically outside the building) and transfer it inside the building (i.e. the air inside the building, or to the water used in a water-borne heating system). Compressors inside the heat pump are used to create a compression refrigeration cycle using a distinct heat transfer fluid. This cycle requires mechanical work which is typically fuelled by electricity.

Since the electricity is not directly used to create heat, but to transfer energy from the heat source to the heat sink, heat pumps feature very high energy performance. The ratio between the electricity consumption of the heat pump and the useful heat supplied to the heat sink is called the *coefficient of performance* (COP). It typical reaches values of 3 and above (Miara, Günther, Kramer, Oltersdorf, & Wapler, 2011). This efficiency varies with the difference of temperature between the heat source and the heat sink: the bigger the difference, the lower is the COP of the heat pump.

Heat pumps are commonly distinguished with respect to the heat source (Fleiter, Steinbach, & Ragwitz, 2016):

- *Air-source heat pumps*. This is the most common type of heat pump. The heat is extracted from the ambient air and transferred to the building. Since the outside temperature varies throughout the year, the efficiency of the heat pump varies accordingly, that is during winter (when the outside temperature is lowest) the heat pump efficiency is lower. Because the heating demand in most of the countries is most important at the same time, air-source heat pumps may lead to important electricity consumption peaks during winter.

- *Ground-source (or geothermal) heat pumps*. A heat exchanger is installed in the ground and connected to the heat pump via loop circulating a heat carrier medium. The heat exchanger is buried into the ground, either horizontally, a few meters deep, or vertically to reach more significant depth where the temperature is both more constant throughout the year and higher. More stable and higher temperatures increase the efficiency of the heat pump, with COPs around 5 (vs 3 for air-source heat pumps). On the other hand, the more complex installation compared to air-source heat pumps implies significantly higher investment costs.

- *Water-source heat pumps*. Water, such as a lake or a river, may alternatively serve as heat source for a heat pump. The more constant temperature may likewise lead to a higher efficiency compared to air-source heat pumps. These systems are however less common than air and ground source heat pumps, since they are only adapted to very specific locations.

Apart from the heat source, the heat sink has a significant impact on the design and operation of the heat pump. The simplest systems release the heat directly into the inside air of the buildings, while more advanced ones transfer the heat to the water central heating systems of buildings. Water-borne heat sinks are divided into two categories, according to the required temperature:

- *High-temperature systems*. The water temperature in a traditional heating system is around 75-85°C. Such heat sink temperatures typically occur in older buildings, with low insulation, requiring medium-size radiators.

- *Low-temperature systems.* In these systems, the water temperature is around 35-55°C. Such temperatures can typically be realised in newly constructed or completely refurbished buildings. Low-temperature heating systems require a specific design, with large radiators or underfloor heating. The lower inlet temperature increases the efficiency of the heat pump (since the COP is greater with a lower difference between the heat sink and the heat source).

Regarding the energy efficiency of heat pump systems, it is important to bear in mind that the installation and the sizing of each system is a crucial step to reach high energy performance. The proper evaluation of the heating demand, an as low as possible heat sink temperature, and a proper maintenance of the heat pump during its lifetime are key to ensure high performances (Miara, Günther, Kramer, Oltersdorf, & Wapler, 2011).

Heat pump systems are rather expensive systems compared to conventional electric appliances or fossil fuel boilers. In order to have a cost-effective system and avoid over-dimensioning, heat pumps are often coupled to a back-up heater, to supplement heat pump during days with featuring very cold temperatures. This holds in particular true for air-source heat pumps, where the COP decreases with the temperature, requiring an important thermal capacity for the coldest days. In this regard, heat pump system can be classified in three categories (Bloess, Schill, & Zerrahn, 2017):

- *Monovalent heat pumps*. The heating system only consists of the heat pump, without a back-up.

- *Monoenergetic heat pumps.* The heating system consists of a heat pump, complemented by an electric back-up heater using the same type of final energy (i.e. an electric boiler).

- *Bivalent (or hybrid) heat pumps.* The heating system consists of a heat pump and a back-up heater fuelled by another energy carrier than electricity (such as gas, oil or biomass).

#### 4.1.2. ***Flexibility***

For the last few years, power production from variable renewable energy sources (vRES, that is wind and solar) has significantly increased and current projections of the power production mix for the next decades foresee even higher share of vRES[5]. The current European production mix is mainly constituted of relatively flexible thermal plants that can follow the demand curve. With higher penetration of vRES, an important part of the power production will be non-dispatchable and additional flexibility will be required to balance power demand and supply at any time.

By coupling the power and heating sector, power-to-heat technologies can have a central role in the integration of more power renewable production as they represent an additional electricity demand that can be temporarily shifted in time to better match the power supply.

This flexibility is often realised thanks to a thermal storage: a dedicated material is heated in advance to store heat which can be released later in time to provide equivalent comfort for users. Depending on the storage size, it is possible to shift demand from a few hours to several days. Seasonal thermal storage is however not possible for decentralised power-to-heat solutions, since it requires large facilities that cannot easily be integrated in buildings. Such long-term storage is only used for district heating.

Heat pump systems are often installed with a thermal buffer storage in order to provide smoother operation, and avoid too frequent on-off cycles that can damage the heat pump. Thus, for instance in Germany most buildings with heat pumps are equipped with thermal

[5] See Section 5.1.1 for more information about the power system scenarios used in this study.

storage tanks (Fischer, 2017). For this short-term flexibility (up to a couple hours), a well-insulated building can be sufficient: The thermal energy is stored in the building mass and is released during the following hours in an uncontrolled way (Bloess, Schill, & Zerrahn, 2017).

Operating power-to-heat installations with thermal storage to provide flexibility proves nowadays still relatively complex, since all systems are not yet systematically equipped with smarts meters, and power markets are not yet fully adapted for these decentralised flexibility solutions. These limitations are not analysed in this study, but detailed information can be found in the literature: (Yilmaz, Hartel, Keles, McKenna, & Fichtner, 2017), (Fischer, 2017).

### 4.1.3. *INVESTMENT COSTS*

Investment costs are a key factor when determining the profitability of a heating system and its competitiveness in comparison with alternative technical solutions. This study analyses the benefits of heat pumps over conventional heating system (represented by gas boilers) and compares the overall system costs related to the comprehensive roll-out of one or the other technology (cf. the different options analysed, listed in Section 5.2).

Heat pump investment costs vary widely from one system to another, especially depending on the type of heat source. Air-source heat pumps feature lowest costs while ground-source heat pumps exhibit highest costs due to the necessary underground drilling work. In this study only air-source heat pump technology with a water distribution system (which is the most commonly used technology) is considered in the assessment. The associated costs (shown in Table 2) are based on a JRC report about the projection of different energy technology indicators until the year 2050 (JRC, 2014).

In this study, all heat pumps are considered to be equipped with a back-up heater: an electric boiler for monoenergetic heat pumps and a gas boiler for bivalent heat pumps (cf. Section 4.2 for the related model description). Their investment costs are based on a benchmark of different manufacturer prices (such as Gretel, Auer or De Dietrich). These prices are assumed to apply to all EU countries. In our scenarios, gas boilers can either be a stand-alone installation, or used as a back-up heater to complement a heat pump during cold days[6]. Investment costs are assumed to be the same in both cases, since the same kind of technology is used.

For heat pumps and gas/electric boilers, a lifetime of 20 years is considered, in accordance with current systems' life-cycles. A discount rate of 8.5% was used to annualise the CAPEX, to be consistent with already existent investment costs present in METIS models (based on discount rates from the European Commission's scenarios).

*Table 2 - Investment costs of different electricity and heat generation technologies*

| | CAPEX | CAPEX (annualised) |
|---|---|---|
| Heat pump | 750 €/$kW_{th}$ | 77 100 €/$MW_{th}$/y |
| Back-up electric boiler | 120 €/$kW_{th}$ | 12 700 €/$MW_{th}$/y |
| Back-up or stand-alone gas boiler | 190 €/$kW_{th}$ | 19 900 €/$MW_{th}$/y |
| OCGT | 550 000 €/$kW_{el}$ | 66 100 €/$MW_{el}$/y |

[6] See section 5.2 for more information about the different options of heat pump configurations analysed in this study.

OCGT investment costs were already included in METIS models, and this same value has been used in the current study.

The listed costs were compared to other sources to ensure their reliability. A recent study prepared in the framework of the ASSET project[7] reveals similar investment costs for heat pumps, electric boilers and gas boilers (Capros, et al., 2018).

## 4.2. HEAT PUMP MODELLING IN METIS

In order to adequately capture the interaction between heat pump utilisation and the EU power system with the METIS power system module[8], additional functionalities had to be added. This applies in particular to the simulation of heat pump behaviour (i.e. appropriately capturing the variation in heat demand throughout the year) and the reflection of the different potential technical configurations of heat pump systems. All heat pumps existing in a country featuring the same configuration are aggregated and modelled as a single asset, representing the same behaviour based on the average hourly national outdoor temperature.

Heat pumps are complex systems, and multiple factors such as the temperature variation of the heat sink/source, or the performance of the different compressors can have a significant impact on the heat production. Very precise analyses of the thermal dynamics can be performed to analyse a single heat pump system, but in the context of a more national power system-related approach with an aggregation of a large number of heat pumps, a more simplistic methodology is more appropriate. The latter should take into account the most important characteristics of heat pumps (such as efficiency of the heat pump or the temperature of the heat sink/source). Hence, this section reveals how heat pumps are modelled in METIS and how the dimensioning of individual heat pump systems is carried out.

Different models are used in the literature to represent the behaviour of heat pumps, depending on the level of detail required. In the present case, the integration of variable renewable energy sources through heat pumps represents a major objective, which is why a model is chosen that takes into account the dependence on the hourly ambient temperature. The model was inspired by the work done in two studies about heat pumps (Liu, Wu, & Petersen, 2013) and (Fischer, 2017).

Generally speaking, the functioning of the heat pumps is simulated by optimising the hourly operation of the nationally aggregated heat pumps and related back-up capacities in order to meet the hourly heat demand at lowest costs, taking into account that heat demand and the heat pump's COP vary in function of the ambient temperature. The operation of the heat pump systems is jointly co-optimised with the hourly dispatch of all European power generation, transmission and storage assets.

### Heating demand

The model assumes a linear relation between the heating demand and the outside air temperature: when the outdoor temperature drops below 16°C, the useful heat demand increases linearly with the decrease of the temperature. At temperatures above 16°C, the heating demand is supposed to be equal to zero.[9]

### Heat pump capacity

[7] ASSET (Advanced System Studies for Energy Transition) is an EU funded project, which aims at providing studies in support to EU policymaking, including for research and innovation.

[8] The METIS power system module features a national granularity. That is, production plants with similar characteristics are aggregated together (e.g. all recent OCGT power plants of a country are represented by a single element, whose production capacity is the sum of all units).

[9] The threshold temperature of 16°C is applied to all countries, based on (Liu, Wu, & Petersen, 2013)

The thermal cycle performed by a heat pump system relies on various components (compressor, thermal fluid, heat exchangers …) whose characteristics vary with the temperature of the heat source and the desired output temperature. The thermal power available for a given system then varies according to the heat source temperature[10]. Manufacturers typically state the thermal capacity at different reference temperatures (often an average temperature during the heating season, and an extreme temperature) to represent the decrease in efficiency with declining temperature. Our model assumes a linear relation between the heat pump capacity and the source temperature (cf. Figure 5). The heat pump capacity is null below -26°C, and all heat is generated via the back-up heater (Liu, Wu, & Petersen, 2013).

**Back-up heater**

Since the heat pump's capacity decreases with lower temperatures, the overall system has to be dimensioned accordingly to ensure that the heating demand is even met at the lowest temperature. This leads to an oversized system, because extreme temperatures are reached only for a couple of hours each year. To avoid over-investments in expensive heat pump systems, almost all installations combine a heat pump with a back-up heater (a simple electric boiler or a fossil-fuel boiler) to supplement heat pump at the lowest temperature. The sizing of this back-up heater is realised in order to cover most of the heat demand by the heat pump, and only use the back-up heater during the coldest days (see explanations further below). The threshold temperature below which the back-up heater has to supplement the heat pump is called the bivalent temperature[11] (cf. Figure 5).

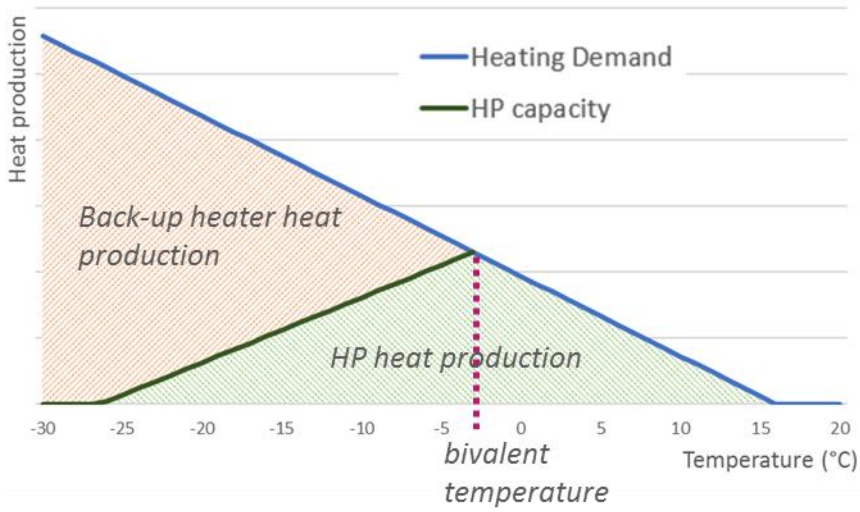


*Figure 5 - Decomposition of the heat production between the (air-source) heat pump and the back-up heater in function of the outdoor temperature (i.e. temperature of the heat source)*

**Heat pump coefficient of performance**

The main advantage of heat pump systems is their high efficiency. This efficiency (COP) however depends on the difference of temperature between the heat source and the output temperature at the heat sink: the greater the difference, the lower the efficiency.

The COP values used in this study are based on (Liu, Wu, & Petersen, 2013) and correspond to air-source heat pump systems. There are in line with current heat pump characteristics across Europe. These values could significantly change in the future with improvement of heat pump technologies, leading to more efficient systems and consequently then lower electricity consumption. Yet, as the technical evolution remains uncertain, this study

[10] The heat source temperature corresponds to the outdoor temperature in case of an air-source heat pump.

[11] In this study, the bivalent temperature applies to both monoenergetic and bivalent heat pumps.

represents a conservative assessment with respect to efficiency improvements, assuming current values for the years 2030 and 2050.

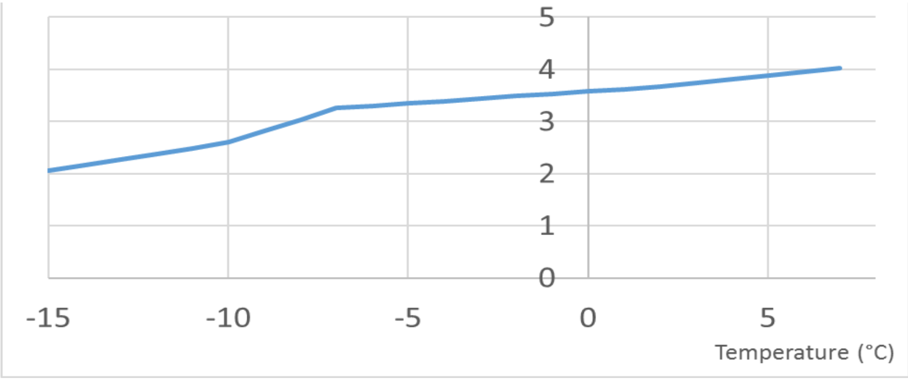


*Figure 6 - Heat pump coefficient of performance (Liu, Wu, & Petersen, 2013)*

Since the COP is always greater than 1, and around 3 on average, heat pumps are always more efficient than a back-up heater, whose efficiency is lower than 1. Thus, the efficiency of the whole system (i.e. heat pump + back-up heater) significantly decreases with a rising contribution of the back-up heater to the heat supply. This is illustrated in Figure 7, where the electricity consumption of the back-up heater is way higher than the heat pump consumption due to the lower efficiency.

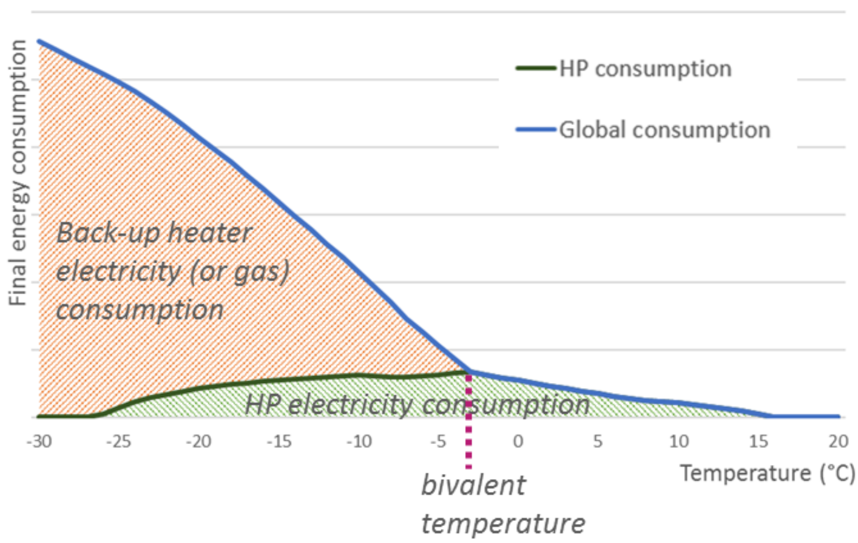


*Figure 7 - Decomposition of the final energy consumption between the heat pump and the back-up heater with the temperature*

This efficiency drop at very low temperatures can also be noted when analysing the temporal evolution of the power consumption[12] of the whole system (heat pump + electric back-up heater), cf. Figure 8. In the illustrated example of heat pump electricity demand in Austria, electricity consumption is close to zero during summer (since the outside temperature is on average above 16°C). In winter, as long as the outside temperature remains above the bivalent temperature, the heat pump can satisfy the whole heating demand. But for the coldest days, when the back-up heater has to supplement the heat pump, power consumption soars, leading to significant power demand peaks during a few days per year.

[12] And gas consumption in case of a gas bivalent heat pump.

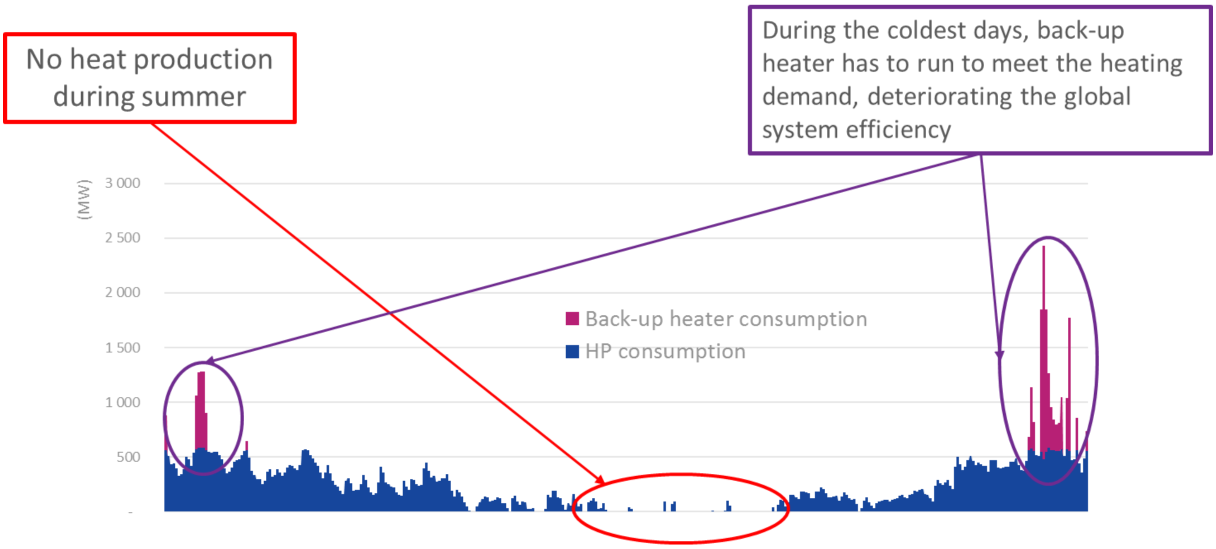


*Figure 8 - Hourly heat pump power consumption in Austria in the REF16-2030 scenario*

**Back-up heater sizing**

As explained before, the sizing of the heat pump system is a trade-off between the CAPEX and the OPEX of the two technologies. A heat pump is a rather expensive equipment, but due to its very high efficiency it ensures heat production at a reasonable price. On the other hand, an electric or gas boiler has lower investment costs but much more important variable costs (in particular fuel costs).

Currently, the sizing differs between monoenergetic and bivalent heat pumps. Given that currently the price for gas is lower than for electricity, the back-up heater of a bivalent heat pump is used more often than the one of a monoenergetic heat pump. Assuming that this price ratio persists in the future, the current back-up sizing rules (based on (Fischer, 2017)) are also used in this study:

- *Monoenergetic heat pump*: 95% of the useful heat demand are covered by the HP and the remaining 5% by the electric back-up heater
- *Bivalent heat pump*: 60% of the useful heat demand are covered by the HP and the remaining 40% by the gas back-up heater

This sizing of the back-up heater was performed individually for each European country, using thirty years of historical temperature data. The result of this sizing is the bivalent temperature for each country for the two types of heat pump (monoenergetic and bivalent), cf. Figure 9. Colder countries have lower bivalent temperatures, meaning that back-up heaters are used at lower temperatures than in warmer countries.

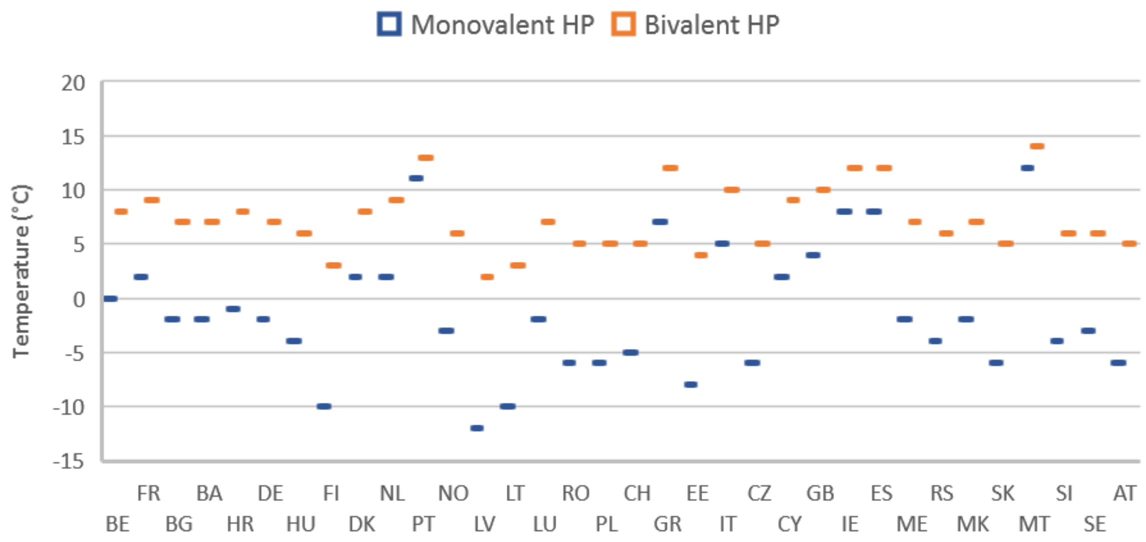


*Figure 9 - Bivalent temperature for European countries*

**Thermal storage**

A water tank is often used as a buffer between the output of the heat pump and the household's central heating system, in order to provide a more reliable heat and to smooth the heat pump operation. Combined with smart meters and time-varying electricity prices, a storage device can provide flexibility with respect to the operation of the heat pump which allows consuming electricity in advance (and at lower prices), store the heat and then release it when required.

In this study, the storage is dimensioned with the objective to store the equivalent of two hours of heat production at full capacity, according to current practices (Fischer, 2017).

In normal operation mode, the thermal storage temperature is rather constant over time, but the temperature slightly changes depending on the ambient temperature. In order to store energy, a signal is sent to increase the working temperature of this storage. During this time when the storage temperature is above normal, thermal losses increase.
In the METIS tool, these losses are represented with a loss rate per hour. Its value has been determined based on a literature review (Fischer, 2017):

$$\textit{Heat loss rate} = 6\%/\textit{hour}$$

The heat loss is expressed as a percentage of the stored thermal energy. Since the stored energy is proportional to the temperature of the water tank, thermal losses vary as a function of the storage temperature.

**The meaning of the term "heat pump" in the remainder of this study**

As explained before, a typical building heated by a heat pump also includes a back-up heater system (an electric boiler for a monoenergetic system, and a gas boiler for a bivalent heat pump). Hereafter, if not specified otherwise, "heat pump" stands for the whole system. That is, the term "heat pump consumption" refers to the energy consumption of the heat pump *and* the back-up heater.

# 5. Scenario-framework for the model-based assessment

To analyse the influence of decentralised heat pumps on the European power system, an analysis is conducted based on the previously defined models. Different options are defined to assess the benefits of different technical heat pump configurations. These options are analysed for two EU power system scenarios: a 2030 "business-as-usual" scenario and a further decarbonised 2050 scenario, with a renewables share of 65% in power production and a high $CO_2$ price.

## 5.1. EU power system and heat pump scenarios

This subsection details the two EU power system scenarios used in the model-based assessment. It further provides information on the decomposition of power demand by end-uses that is realised to isolate the heat pump electricity consumption from the other end-uses.

### 5.1.1. *European power system scenarios*

The METIS software includes a set of pre-calibrated scenarios based upon the official European Commission's scenario data (Artelys, 2016). Two scenarios of the European power system are used in this study to analyse the future role of decentralised heat pumps:

- The **2030 business-as-usual Scenario (REF16-2030)** represents the European Commission's *Reference Scenario* for 2030 (European Commission, 2016). It includes all policies and measures adopted at EU level and in Member States (MSs) by December 2014 and meets the 2020 but not the 2030 targets for RES deployment, energy efficiency and emission reduction. The RES share in net electricity production is about 42% (cf. Figure 10). This scenario assumes a $CO_2$ price of 33 €/$t_{CO2}$.

- The further decarbonised **2050 scenario (EUCO30-2050)[13]** is based on the European Commission's *EUCO30-2050* scenario, and has been developed to reach all the 2030 targets agreed by the October 2014 European Council (at least 40% reduction in greenhouse gas emissions with respect to 1990, 27% share of RES in final energy consumption and 30% reduction in the primary energy consumption) and the 2050 decarbonisation objectives, continuing and intensifying the current policy mix.RES share in final electricity demand is about 65% (cf. Figure 10). This scenario assumes a $CO_2$ of 522 €/$t_{CO2}$.

[13] At the time of writing the report, this is the latest available scenario from the European Commission for the year 2050.

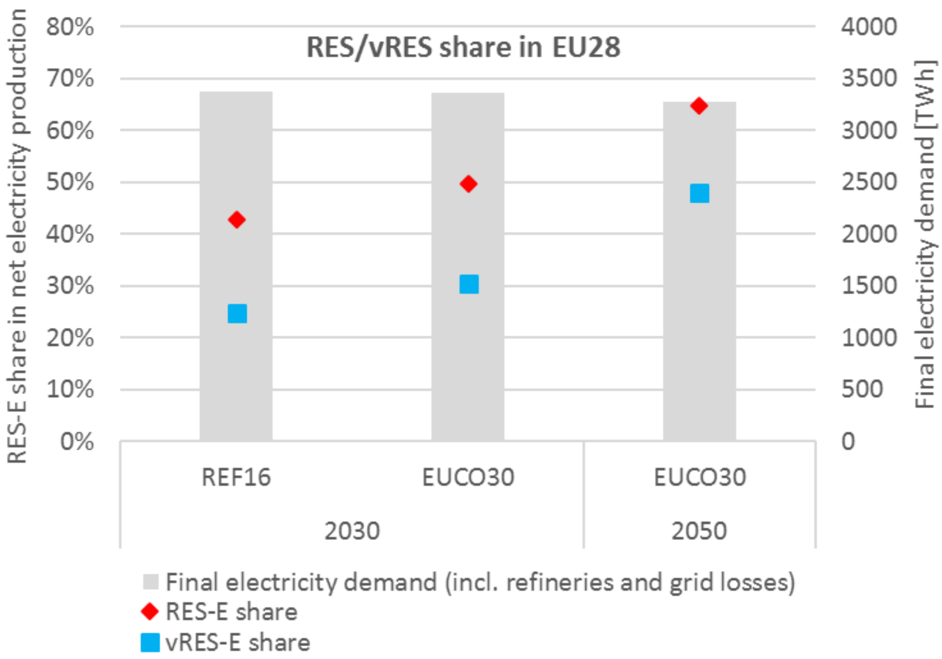


*Figure 10 - RES share and final electricity demand across the different METIS scenarios*

### 5.1.2. ***End-use decomposition of the power demand***

A decomposition of the annual power demand for the above defined scenarios is realised in parallel of this study, in order to have a better grasp of the different end-uses, in particular with respect to heat pumps. This decomposition is based on historical data, and aims at giving an hourly demand profile for each end-use and for each prospective scenario. A dedicated work has also been done to handle new end-uses and the influence of the temperature for thermosensitive end-uses (such as heat pumps) on their electricity consumption profile.

The main objective of this decomposition is to analyse the extent to which each end-use contributes to the overall hourly system load curve. Especially for prospective scenarios, this decomposition is an important prerequisite in order to analyse how different end uses can contribute to enhance power system flexibility (via Demand Response schemes) and how changes in annual power demand of the end-uses affect the occurrence and intensity of load peaks.

The annual consumption by end-use and by scenario (REF16-2030 and EUCO30-2050) are used to modulate the demand profile of each end-use according to the temperature for the different weather realisations.[14]

In this study, the decomposition was used to separate the power consumption associated to the heat-pumps from the other end-uses. In this study, the analysis is limited to decentralised heat pumps for the residential and tertiary sector.

### 5.1.3. ***Recalibration of heat pump scenario data***

To recall, annual power consumption for heat pumps in each scenario is based on the European Commission's scenario data. A thorough review of the data revealed inconsistencies compared to historic data and with respect to the demand evolution across the different scenarios. Hence, a recalibration was carried out based on the JRC-IDEES

[14] A dedicated technical note about the methodology behind the demand decomposition is forthcoming and will be made available in due course on the METIS website https://ec.europa.eu/energy/en/data-analysis/energy-modelling/metis.

energy database[15] which gathers historical data about the European energy sector (Mantzos, et al., 2018).

For some countries, heat pump consumption estimated in the European Commission's scenarios for the year 2015 was lower than historical data. For these countries, the heat pump consumption was resized in order to meet historical values but the evolution between 2015 and 2030/2050 was used to keep the original European Commission's vision of the prospective evolution of heat pump systems (cf. Figure 11).


*Figure 11 - Recalibration of PRIMES heat pump consumption using JRC-IDEES database*

The calibration process has also revealed a number of inconsistencies with respect to the evolution of heat pump-related electricity demand (e.g. the heat pump consumption exceeds the total electricity consumption related to space heat supply or an unrealistically strong increase of heat pump numbers in the future). Specific actions were taken to correct these consumptions, ensuring a more realistic evolution of the heat pump consumption. This includes the assumption that the share of heat pumps in the entire electricity consumption for space heating should not exceed 80%.[16] Figure 12 illustrates the heat pump consumption for all scenarios and all countries after the data recalibration.

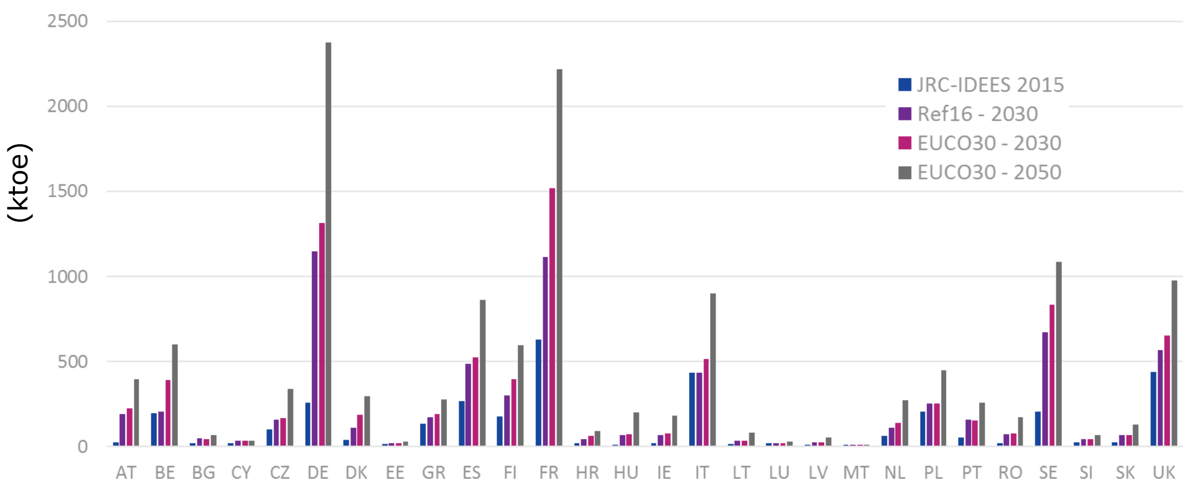


*Figure 12 - Heat pump electricity consumption (after data corrections)*

The determined electricity consumption reveals that by 2030, the installed capacity of heat pumps will nearly double compared to today (cf. Table 3)., reaching some 100 $GW_{th}$. Between 2030 and 2050, this number is assumed to double again, reaching 215 $GW_{th}$ by 2050.

[15] A preliminary version of the database was used for the preparation of this report.

[16] This figure represents the fact that some buildings cannot be equipped with heat pumps, and conventional convectors would not be replaced (for instance in historical buildings where an outside heat exchanger cannot be installed, or secondary residence where heat pump would never been profitable).

*Table 3 - Installed heat pump capacities and consumption for EU28+6 ($GW_{th}$)*

| Option | 2015 | REF16-2030 | EUCO30-2050 |
|---|---|---|---|
| HP capacity ($GW_{th}$) | 54 | 101 | 215 |
| HP electricity consumption (TWh) | 41 | 78 | 172 |

The electricity consumption of heat pumps is finally used to calibrate the METIS heat pump model. We assume that in the European Commission scenarios, all heat pumps are monoenergetic, with the characteristics defined in Section 4.2.

### 5.2. FOUR OPTIONS TO CAPTURE POSSIBLE HEAT PUMPS FUTURE PENETRATION

Based upon the REF16-2030 and EUCO30-2050 scenarios, different options have been designed to analyse different possible variations of heat pump diffusion, derived from the following three objectives:

- Assess the system-wide benefits of heat pumps compared to conventional space heating appliances (i.e. gas boilers) **(1)**
- Estimate flexibility offered by smart heat pumps with thermal storage compared to "uncontrolled" heat pumps **(2)**
- Quantify the impact of bivalent heat pump systems on the power system compared to monoenergetic heat pumps **(3)**

The original REF16-2030 and EUCO30-2050 scenarios represent the central reference option (named **Option A**). That is, all heat pumps are air-source and monoenergetic, without smart metering.

To evaluate the benefit of heat pumps compared to conventional space heating appliances (Objective 1), an **Option 0** has been created where heat pump consumption is identical to current values (based on JRC-IDEES 2015 values). Since REF16-2030 and EUCO30-2050 scenarios have higher heat pump consumption than in 2015, the differential heating demand is supposed to be covered by conventional space heating appliances, namely gas boilers (cf. Figure 13). This option does not aim at representing a possible future for power-to-heat, but represents a hypothetical variant without further heat pump development, to evaluate their benefits by comparing Options A and 0.

**Option B** is a variant of Option A, where each heat pump is coupled to a storage system (cf. storage characteristics explained in Section 4.2). The whole system can be controlled thanks to appropriate smart metering and control infrastructure, and thus provide flexibility to the power system (in line with Objective 2).

With a 100% electric consumption, monoenergetic heat pump risk having negative impacts on the power demand peak. During the coldest days, the electric back-up heaters have to run to supplement the heat pumps, and tend to drastically deteriorate the efficiency of the whole system. Combined with a higher heating demand at lower temperatures, monoenergetic systems increase power peaks, implying a potential need for additional investments in peak power production capacities to meet power demand at any time. **Option C** is designed to alleviate the impact on power demand peaks by replacing 30% of all heat pumps of option B by bivalent heat pump systems, where gas back-up heaters take over the heating supply during the coldest days (in line with Objective 3).

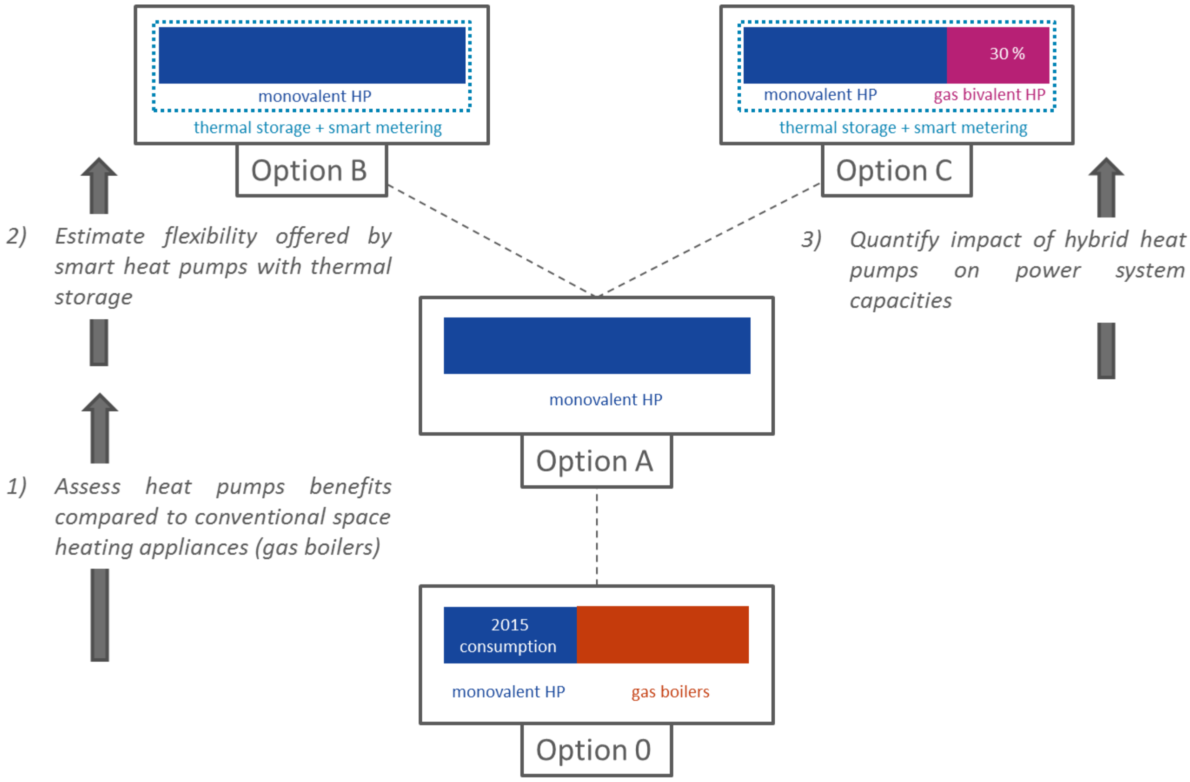


*Figure 13 - Options definition*

## Results analysis methodology for the model-based assessment

As explained before, the model-based assessment aims at analyse the benefits of heat pumps under different technical configurations. Three initial objectives or research questions were initially introduced which are answered by means of the modelling results in the following Sections 6, 7 and 8.

Each research question is analysed by comparing results of two options (cf. Figure 13). To simplify the results presentation, the analysis is divided in two parts:

- The two options are first compared for the REF16-2030 scenario. The heat pump configuration evolution is analysed, and the main findings are explained.
- Then the comparison of the two options is realised for the EUCO30-2050 scenario. This part focusses on highlighting the differences between the two scenarios, i.e. how the characteristics of each scenario (RES penetration, $CO_2$ price, etc.) affect heat pumps integration and the overall power system.

In METIS, the power system is modelled for 34 European countries (all ENTSOE members[17]). Consequently, all quantitative results ($CO_2$ emissions, power consumption, investment costs etc.) are shown for the whole of the 34 modelled countries, if not explicitly stated otherwise.

[17] The 28 Member States of the European Union, plus Bosnia and Herzegovina, FYR of Macedonia, Montenegro, Norway, Serbia and Switzerland

# 6. BENEFITS OF HEAT PUMPS COMPARED TO CONVENTIONAL SPACE HEATING APPLIANCES *(OPTION A VS 0)*

With a typical efficiency of 3, heat pumps are by far the most efficient heating system. When used to replace an older heating system (such as fossil-fuelled boiler) during a building renovation, heat pump can lead to up to 75% energy reduction with the most efficient models (ground-source heat pump with low temperature heating system).

With more than 40% and 65% of renewable energy in the power mix for both REF16-2030 and EUCO30-2050 scenario, respectively, heat pumps can also benefit from the low-carbon electricity to decrease global $CO_2$ emissions compared to conventional heating system, such as gas boilers.

However, investment costs in heat pumps are more than three times more important than for gas boilers, questioning the profitability of such investments. In the following, we will analyse for both, the REF16-2030 and the EUCO30-2050 scenario, the benefits of heat pumps compared to gas boilers and their overall profitability.

## 6.1. REF16-2030 SCENARIO

### 6.1.1. *$CO_2$ EMISSIONS DECREASE WITH HEAT PUMPS*

With an efficiency above 3 for heat pumps, and a power generation covered by 42% by renewable energy, a first thought would be that heat pumps would drastically cut $CO_2$ emissions generated by conventional gas boilers. However, $CO_2$ reduction between Option A and Option 0 represents only about a third of the total emissions of gas boilers in Option 0 (7 Mt over 23 Mt, cf. Figure 14). For this analysis, we assume that the heat pump development policy is not accompanied by the construction of additional low-carbon power generation capacities. In that case, the additional power demand is supplied by existing thermal capacities such as coal, lignite and gas units. Nuclear capacity also contributes but to a limited extent, as it already runs almost at full capacity in Option 0.

This 7 Mt emission reduction represents around 1% of the whole $CO_2$ emissions of the power sector in Europe. Even if this number appears to be rather small, a fully decarbonised power mix would allow tripling emission reduction through heat pumps, as the blue bars in Figure 14 would disappear.

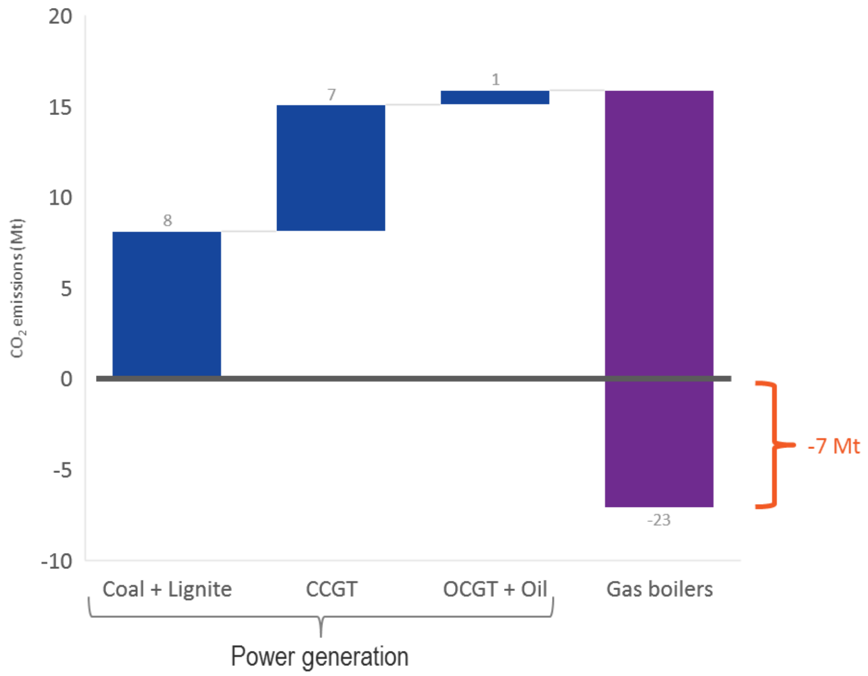


*Figure 14 - $CO_2$ emissions in scenario REF16-2030 (option A vs option 0)*

### 6.1.2. ***POWER CONSUMPTION PEAKS INCREASE***

Between Option 0 and Option A, heat pump capacities are installed to replace gas boilers. The related increase in power consumption (cf. Figure 15) is not constant over time but peaks when the temperature is lowest, i.e. in winter. Since power demand of Option 0 is already the highest during winter time in most of the EU countries, this means that the consumption peak of the additional heat pump capacities adds up to the pre-existing power demand peak.

Consequently, the demand peak increases in all countries, as shown in Figure 16. In order to cope with this higher peak demand, the power system has to be adapted:

- Additional peak capacities (OCGT) are necessary to satisfy the demand during the coldest days.
- Further infrastructure investments would be necessary at the electricity distribution and transportation level, to handle this higher load.[18]

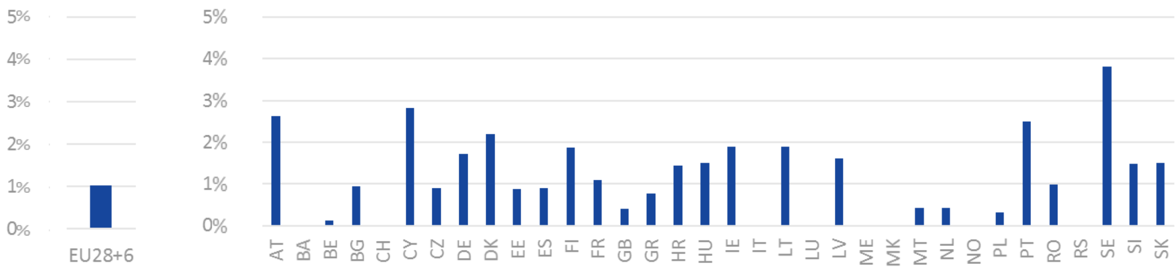


*Figure 15 - Power consumption increase in scenario REF16-2030 (option A vs option 0)*

[18] In this study, infrastructure investments in gas and electricity networks are not reckoned. Further analysis should be conducted to properly asses how these investments could affect the profitability of the different options.

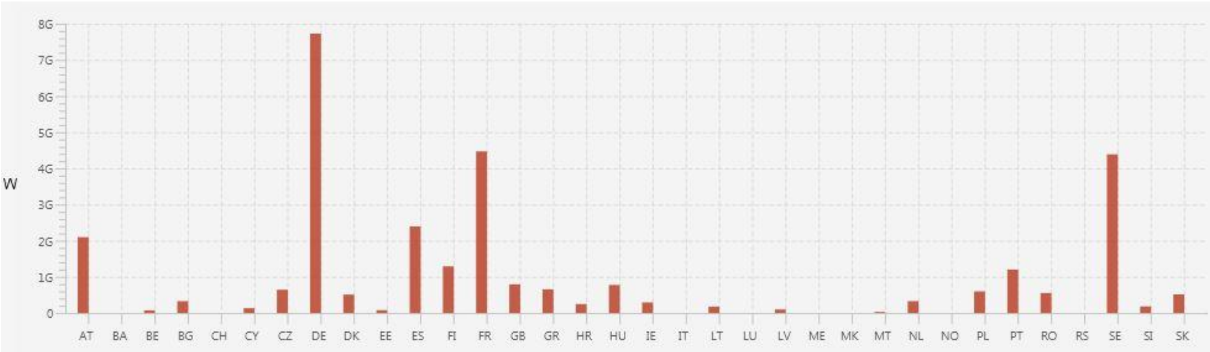


*Figure 16 - Increase in power consumption peaks related to additional heat pumps in scenario REF16-2030 (by country, Option A vs 0)*

It is important to note that a higher demand peak does not necessarily imply the need of additional peak units. Indeed, the production of variable renewable production could also be in phase with this peak, and then no additional flexibility needs would be necessary[19]. For the specific case of heat pumps, it would be necessary to have a high solar and wind production during the coldest days. Thanks to asynchronous demand peaks in Europe, interconnections could also reduce the need for additional capacity. For the sake of robustness, the worst case was considered in this study: the extra peak demand of the heat pumps is directly into a corresponding peak capacity requirement.

### 6.1.3. ***PROFITABILITY***

Heat pump investment costs are three times higher than those for gas boilers. With the additional peak units necessary to satisfy the demand during the coldest days, and from a system perspective, Option A relying on heat pumps appears to have more important capital expenditures than Option 0, relying on conventional gas boilers (cf. CAPEX part of Figure 17).

At the same time, the substitution of gas boilers with heat pumps under Option A leads to a significant reduction in gas purchase costs[20] (4.7 bn€), while power production costs increase only by 2.5 bn€. However, these 2.2 bn€ of net OPEX savings cannot counterbalance the 4.0 bn€ of additional investment costs. Hence, the shift towards heat pumps implies total extra costs of 1.8 bn€. Thus, heat pump expansion reduces emissions by 7 Mt $CO_2$ annually at extra costs of 1.8 bn€.

[19] More information about flexibility needs in a context of high variable renewable share can be found in METIS study S11 (Artelys, 2018).

[20] Gas prices are based on the European Commission's Reference Scenario, assuming 30.8 €/MWh in 2030 and 35.3 €/MWh in 2050.

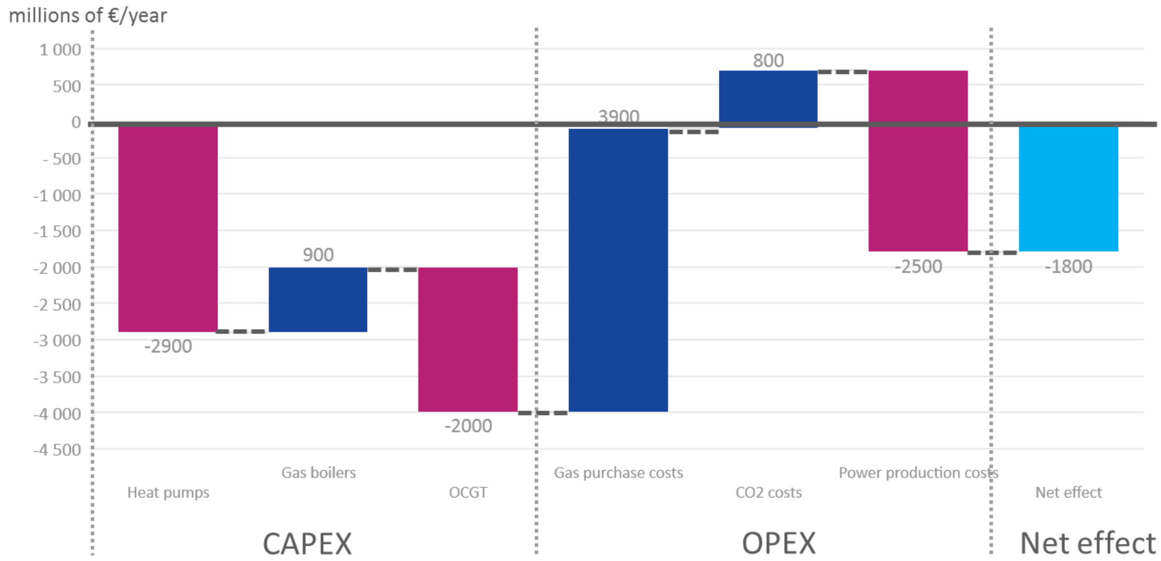


*Figure 17 – Economic benefits of Option A vs Option 0 in the REF16-2030 scenario*

## 6.2. EUCO30-2050 SCENARIO

### 6.2.1. $CO_2$ EMISSIONS DECREASE WITH HEAT PUMPS

With a RES share of 65% (and thus 50% more renewable production than the REF16-2030 scenario), the power mix of the EUCO30-2050 scenario is even further decarbonised. In addition, a higher $CO_2$ price (522 €/$t_{CO2}$ in the EUCO30-2050 scenario vs 33 €/$t_{CO2}$ in the REF16-2030 scenario) changes the merit order and thus the base load composition of the European power mix: while coal and lignite power plants used to be an important part of the power base-load, the higher $CO_2$ price shifts them out of the market, paving the way for low-carbon nuclear, renewable energy and gas capacities to meet the bulk of demand. Figure 18 illustrates the change in $CO_2$ emissions due to the shift towards heat pumps. The major part of emissions increase is related to the additional power production from mid-merit gas plants (CCGT) and peakers (OCGT and oil).

This leads to lower additional $CO_2$ emissions from the power production in EUCO30-2050 scenario than in REF16-2030 scenario (in proportion): In EUCO30-2050 scenario, net $CO_2$ emission savings sum up to 45 Mt, which represents 60% of the whole gas boilers $CO_2$ emissions (compared to 7 Mt in the REF16-2030 scenario, which represents 30% of the whole gas boilers $CO_2$ emissions).

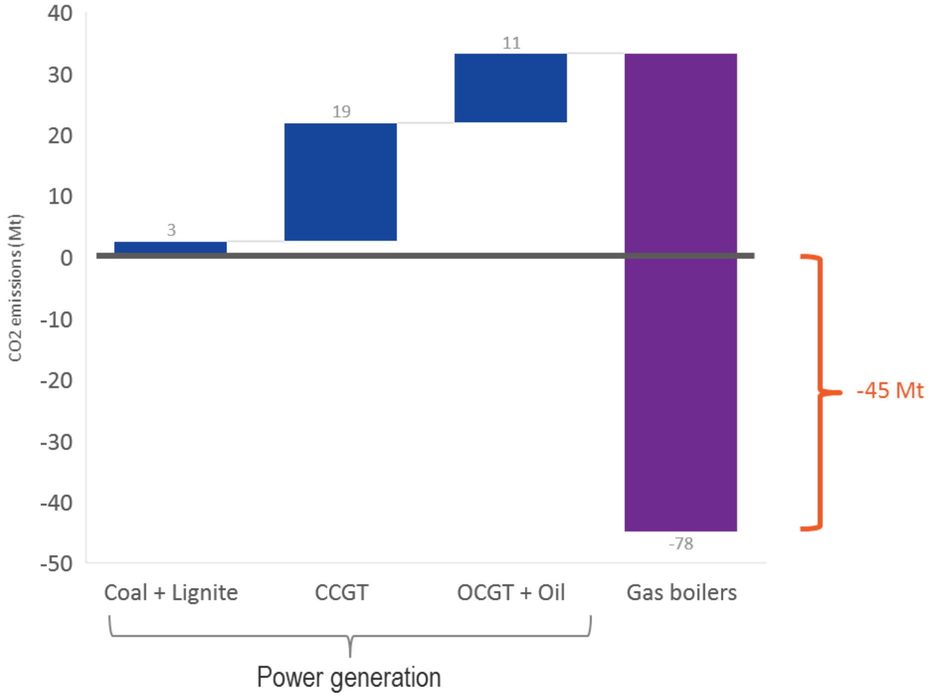


*Figure 18 - CO2 emissions in scenario EUCO30-2050 (option A vs option 0)*

### 6.2.2. *POWER CONSUMPTION PEAKS INCREASE*

The increase in power consumption (cf. Figure 19) and the related demand peaks (cf. Figure 20) in the EUCO30-2050 scenario between Option A and Option 0 follows exactly the same pattern across all countries than in the REF16-2030 scenario. The only difference consists of the level of increase. The installed heat pump capacity is more than two times higher in EUCO30-2050 than in REF16-2030 (215 $GW_{th}$ vs 101 $GW_{th}$), thus power consumption peaks also grow by the factor of two.

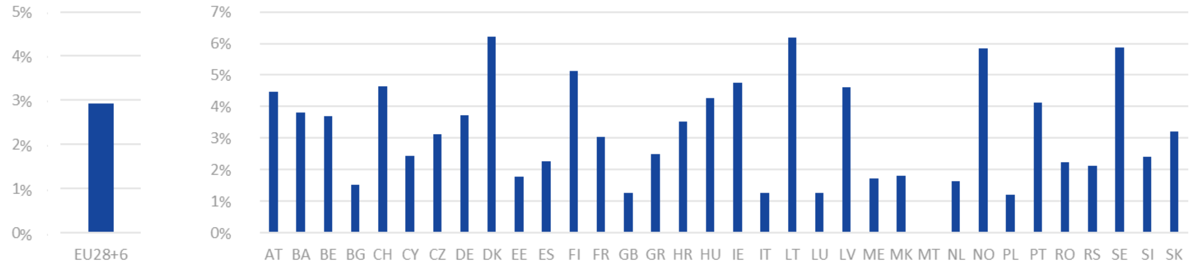


*Figure 19 - Power consumption increase in scenario EUCO30-2050 (option A vs option 0)*

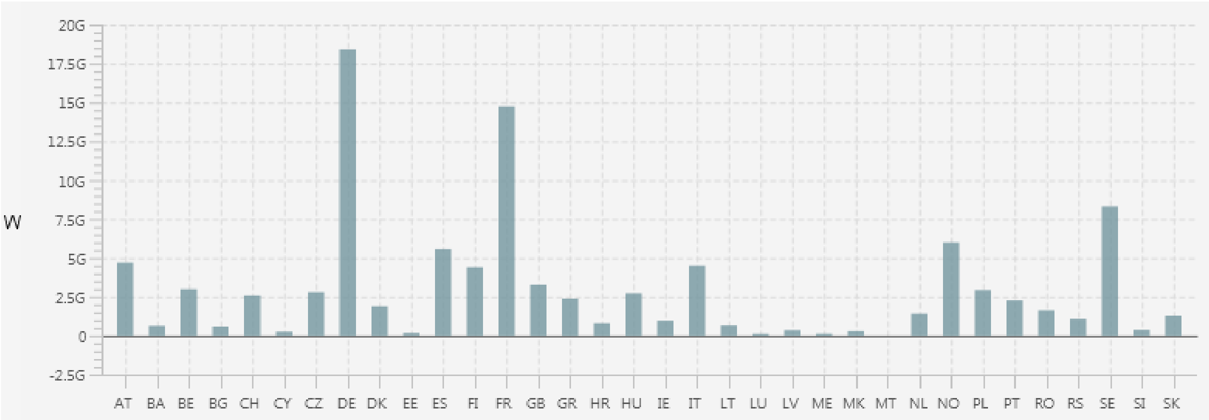


*Figure 20- Increase in power consumption peaks related to additional heat pumps in scenario EUCO30-2050 (by country, Option A vs 0)*

### 6.2.3. PROFITABILITY

Regarding capital expenditures, there is no structural difference between the EUCO30-2050 and the REF16-2030 scenario: only the number of heat pumps varies between them, and required additional capacities follow the same logic (cf. Section 6.1.2).

What matters is the difference in operational expenditures. The additional power production costs necessary to cover the increased heat pump power consumption are entirely offset by the $CO_2$ emission savings thanks to lower gas consumption. While costs under the REF16-2030 scenario were mainly due to the gas market price, with only a small part dedicated to the $CO_2$ price, under the EUCO30-2050 scenario almost ¾ of the gas costs savings are associated to the $CO_2$ price (cf. Figure 21), driven by the very high $CO_2$ price of 522 €/t.

In the EUCO30-2050 scenario, the savings in operational expenditure consequently become so important that they counterbalance the increase in capital expenditures. That is, in this context, installing heat pump capacities instead of conventional gas boilers is a profitable option.

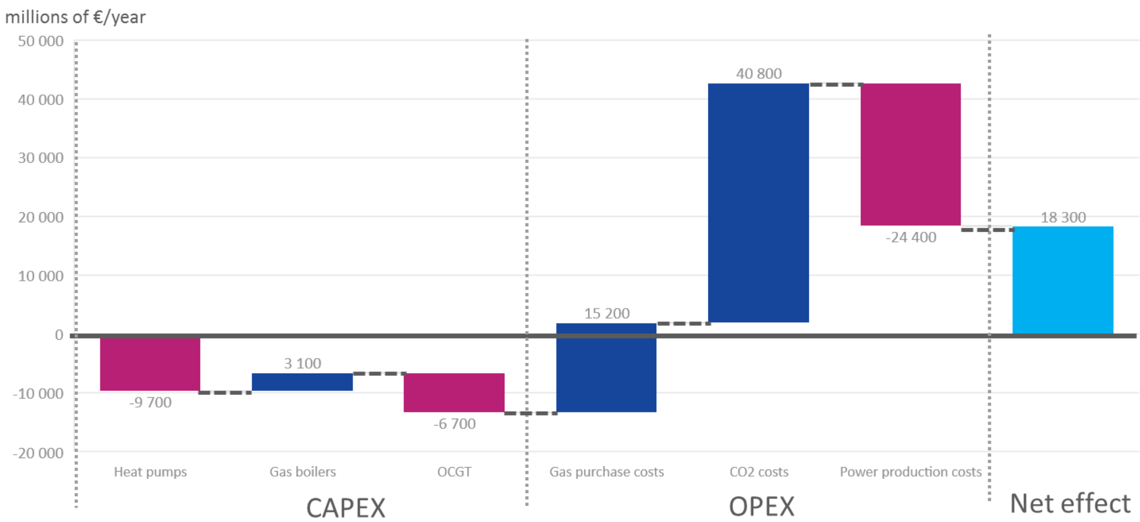


*Figure 21 – Economic benefits of option A vs option 0 the EUCO30-2050 scenario*

## 6.3. VARIANT OF EUCO30-2050 SCENARIO WITH A LOWER CO2 PRICE

**What is the impact of a $CO_2$ price of 100 instead of 522 €/t $_{CO2}$?**

As shown before, the profitability of heat pumps over gas boilers strongly relies on the savings in operational expenditures between the two options. With a very high $CO_2$ price the reduced gas consumption in Option A vs option 0 is converted into important savings that may counterbalance additional CAPEX expenditures (cf. Figure 21).

In order to analyse the influence of a lower $CO_2$ price, a variant of the EUCO30-2050 scenario is assessed, where the only difference is a $CO_2$ price of 100€/t instead of 522€/t. Even if the investment dynamic of power production units is not captured by this variant, it can represent accurately the evolution of the merit order and thereby, the power generation mix. Hereafter, this scenario is named 2050-Variant.

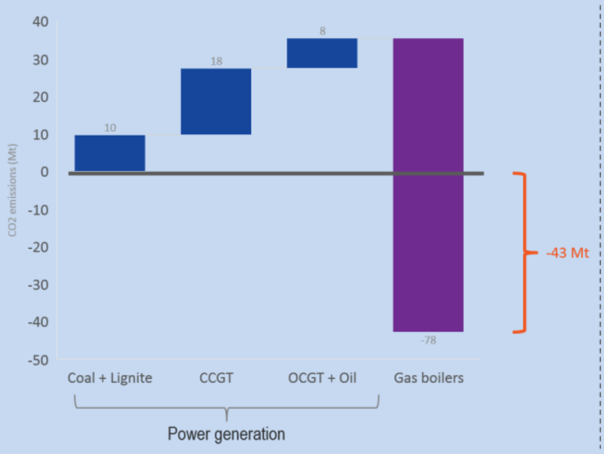


*Figure 22 - $CO_2$ emissions in scenario EUCO30-2050 scenario (Option A vs Option 0)*

With a lower $CO_2$ price, lignite and coal plants have lower marginal costs than OCGT in various countries[21], and are hence used before OCGT units. Thus, part of the additional heat pumps' power consumption is met by these two $CO_2$ intensive power assets (cf. Figure 22), while the remaining part is still met by gas fleets (CCGT) and peakers (OCGT+oil). In sum, $CO_2$ emissions savings drop marginally to 43 Mt compared to 45 Mt in 2050.

Investment costs remain unchanged in the EUCO30-2050 scenario and the variant. Yet, operational expenditures are affected by the differences in power production and $CO_2$ costs. The lower $CO_2$ price dampens the cost savings related to the replacement of gas boilers, while production costs from the mostly green power mix are much less affected. Ultimately, the shift towards heat pumps under this variant is not profitable.

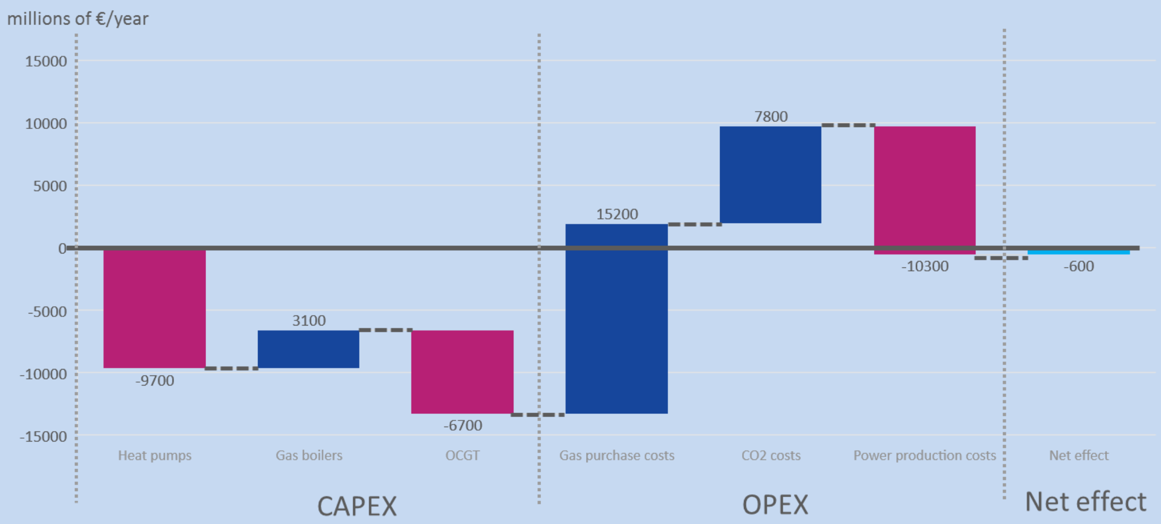


*Figure 23 - Benefits of Option A vs Option 0 in EUCO30-2050 Variant (100 €/t$_{CO2}$)*

# 7. Flexibility offered by smart heat pumps with thermal storage (Option B vs A)

In Option B, all heat pumps are coupled with a two-hour thermal storage capacity. Such storage units are actually common in recent heat pump systems, where a buffer tank is used to avoid too short on-off heat pump cycles. In a future with increasingly well insulated buildings, the hot water circuit may be sufficient to provide this two-hour storage capacity.

The purpose of option B is to analyse if heat pump flexibility can help integrate more low-carbon base-load units, and to quantify the associated cost and emission savings.

## 7.1. REF16-2030 scenario

### 7.1.1. *Daily flexibility*

With a limited storage capacity (only two hours) and relatively high losses (6% per hour), heat pumps with thermal storage can only provide daily flexibility to the power system.

In Option A, with non-flexible heat pumps, we assume that the power consumption is constant during the day. In Option B, the average consumption per hour of the day (cf. Figure 24) is lower during morning hours (around 7am to 8am), and in early evening hours (around 6pm to 7pm). This corresponds to hours where in average the electricity prices are the highest. That is, electricity demand is shifted from peak hours to low price periods. Since thermal losses are relatively high, the demand is only shifted a few hours back in time, to the very early morning and early afternoon hours (see the demand peaks illustrated in Figure 24).

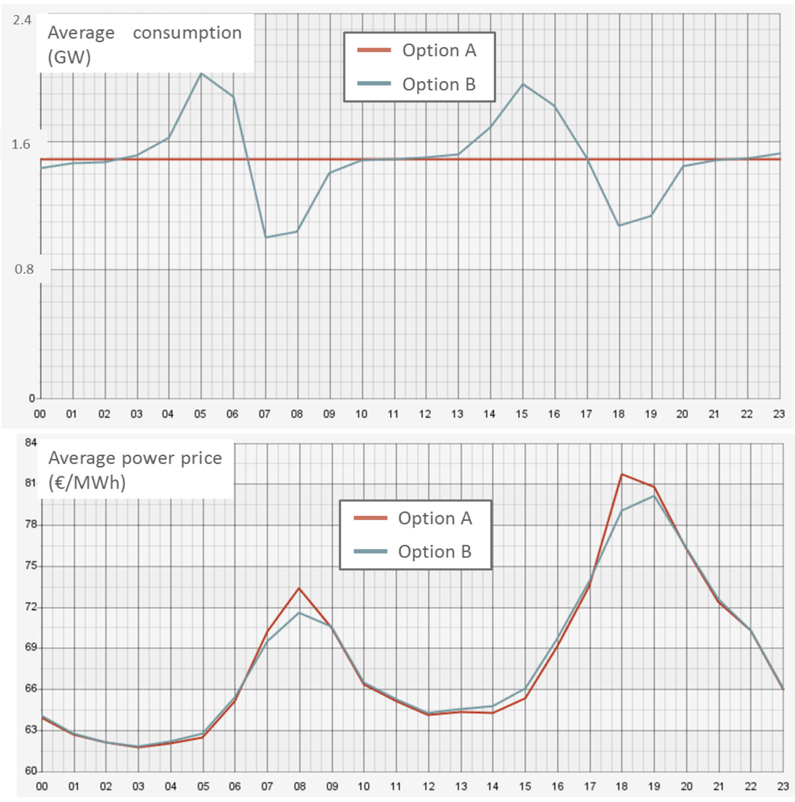


*Figure 24 – Top: Average heat pump electricity consumption per hour of day for Germany in REF16-2030 scenario*
*Bottom: Average electricity price per hour of day for Germany in REF16-2030 scenario*

[21] Please refer to Annex 11.1 for $CO_2$ emissions evolution by country.

### 7.1.2. *INTEGRATION OF BASE-LOAD UNITS AND RENEWABLE ENERGY SOURCES*

The load shifting capability of heat pumps represents an effective way to enhance power production from units featuring lower variable costs. The utilisation of base-load units such as wind, solar, nuclear and (in selected countries) CCGTs is increased (to load the thermal storage), while the production from mid-merit plants and peakers such as coal, OCGT, biomass and pumped storage diminishes (cf. Figure 25). The increase in RES generation is due to an increase in RES curtailment and thus demonstrates the contribution of smart heat pump operation to enhanced RES integration. For the dataset used in this study, the shift between CCGT and coal does only occur in selected countries and for specific power plant clusters (which are grouped by age) where the variable costs from CCGT are lower than those for coal[22], due to a favourable price spread between gas and coal or a favourable difference in the energy conversion efficiency. On average among all countries and clusters, coal units have higher production costs than CCGT, implying that the flexibility offered by heat pumps with thermal storage induces a lower power production of coal units, in favour of CCGT plants.

Using heat pumps to shift load comes with increased losses in the thermal storage. Thus, Option B requires more power production than Option A to cover these losses. This effect is shown by the light blue bar in Figure 25.

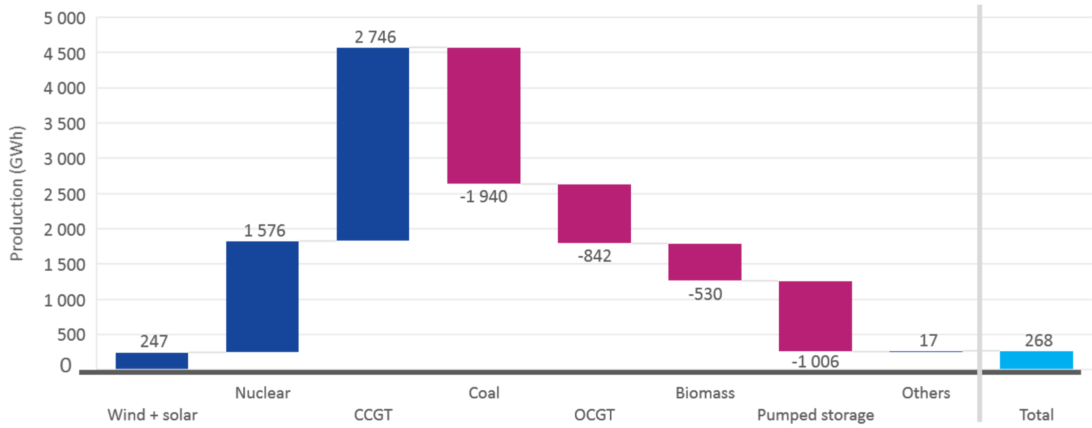


*Figure 25 - Power production in scenario REF16-2030 (Option B vs Option A)*

### 7.1.1. *SAVINGS RELATED TO THE SMART OPERATION OF HEAT PUMPS*

The enhanced utilisation of RES, nuclear and low-carbon CCGTs have two positive effects: lower $CO_2$ emissions of 1 $Mt_{CO2}$ (0.1% of overall $CO_2$ emissions) and production costs savings of 120 M€ (0.1% of overall production costs) between Option B and Option A (cf. Table 4).

It is possible to break these savings down to an individual household[23], considering an average installed capacity for space heating of 5-15 $kW_{th}$. Indeed, smart meters in combination with a real time pricing scheme would enable private individuals to benefit from the variation in wholesale electricity prices, and thus be remunerated by the price spread between peak and off-peak hours.

[22] Including $CO_2$ costs and fuel costs.

[23] In our scenarios, heat pumps consumption covers both residential and tertiary sectors. However, it is possible to estimate an average consumption per household, as if the whole consumption was from residential heat pumps.

These savings per household would be around 6-18 €/year[24]. In Option B, the sizing of the thermal storage is very conservative, and is almost the same as what is currently installed in current buildings for residential and tertiary sectors. However, these savings are likely to be sufficient to recover the costs related to the installation of the smart meters system, considering the entire lifetime of the latter.

*Table 4 - Savings under Option B compared to Option A in the REF16-2030 scenario*

| | Option B vs option A |
|---|---|
| $CO_2$ emission savings | 1 Mt/y |
| Production cost saving | 120 M€/y |
| Production costs saving per $MW_{thermal}$ of smart heat pump | 1 200 €/$MW_{thermal}$/y |
| Savings per household | 6-18 €/household/y |

## 7.2. EUCO30-2050 SCENARIO

### 7.2.1. *DAILY FLEXIBILITY*

The storage size is the same in EUCO30-2050 and REF16-2030 scenario, limiting the flexibility offered by the heat pump storage to daily cycles.

Figure 26 illustrates the mean demand profile of the heat pumps for Germany. The heat pump thermal storage is overheated around two hours before the morning electricity consumption peak, and then used around 7am to 8am to cover the reduce electricity consumption during peak hours.

However, the higher penetration of solar production in the EUCO30-2050 scenario changes the evening cycle. Instead of being overheated two hours before the evening peak, the heat storage is charged around midday to benefit from the low power prices driven by solar generation. The price spread between noon and the evening peak is sufficiently high to recover the related thermal losses from the longer storage time (five hours instead of two, cf. Figure 26 vs Figure 24).

[24] This was calculated by dividing the 120 M€ savings by an estimation of the number of heat pumps. The latter was determined by dividing the total installed heat pumps capacity (54 $GW_{th}$) by the average installed capacity for space heating, which ranges between 5 and 15 $kW_{th}$.

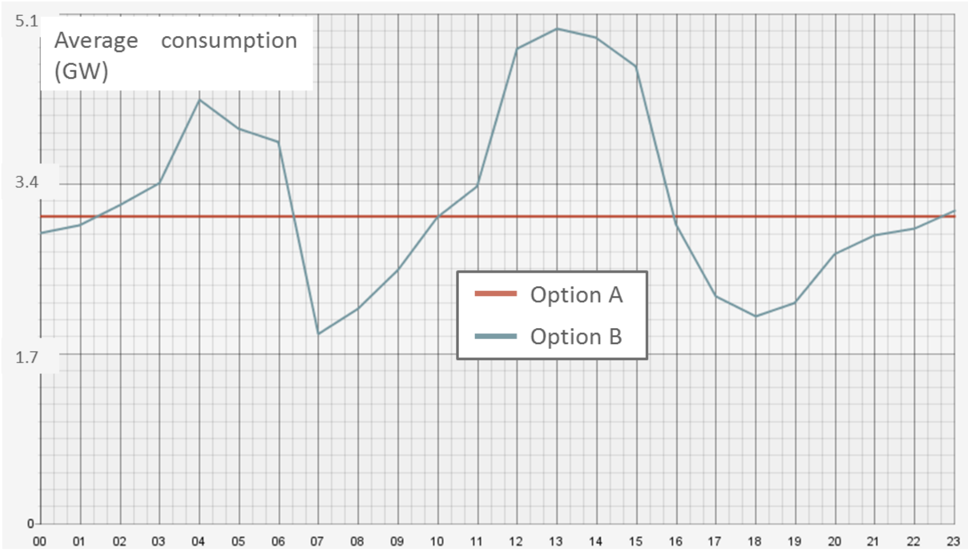


*Figure 26 - Average heat pump electricity consumption per hour of day for Germany in EUCO30-2050 scenario*

#### 7.2.2. ***Integration of base-load units and renewable energy sources***

The EUCO30-2050 scenario exhibits nearly twice the production from variable renewables compared to the REF16-2030 scenario. This implies a reduced utilisation of nuclear base-load units when hourly demand is fully met by RES generation (on a national level), but this also leads to higher amounts of curtailed RES production when national power systems are saturated and cannot integrate the entire RES generation.

This curtailment of RES production is relatively low in the REF16-2030 scenario, with around 1 TWh, but in EUCO30-2050 scenario, it reaches up to 5% of the European RES generation. In such a context, the flexible operation of heat pumps with thermal storage may have a large potential to efficiently integrate renewable power generation.

In the EUCO30-2050 scenario, between Option B and Option A, around two thirds of the whole power production shift are driven by the enhanced integration of renewable power production. The curtailment of around 9 TWh of wind and solar production is avoided, cf. Figure 27. In addition, the utilisation of nuclear capacities and biomass plants is increased, raising their production by 6 TWh (1% increase) and 1.4 TWh (1% increase), respectively. This increase in generation helps decrease the use of more carbon-intense gas peakers and coal capacities as well as the relatively costly utilisation of pumped storage plants.

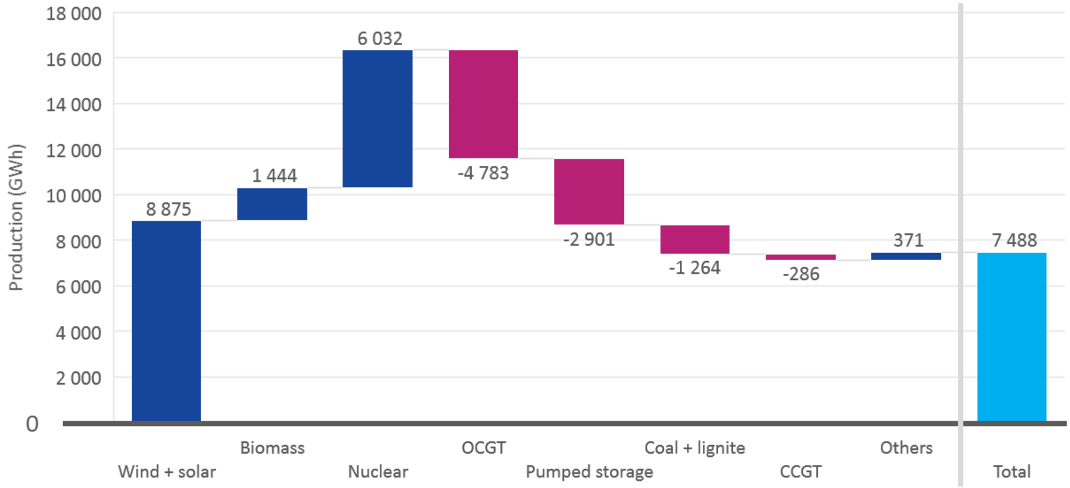


*Figure 27 - Power production in scenario EUCO30-2050 (Option B vs Option A)*

As explained before, the better integration of solar production to meet the evening consumption peak comes at the cost of additional thermal losses. Hence, one may observe a net increase in the power production in Option B compared to Option A, to meet the thermal losses.

### 7.2.3. SAVINGS RELATED TO THE SMART OPERATION OF HEAT PUMPS

The $CO_2$ savings related to the smart operation of heat pumps of 3 Mt $CO_2$ are relatively similar the EUCO30-2050 scenario compared to the REF16-2030 scenario (with respect to the installed capacity of heat pumps, which is more than two times higher in EUCO30-2050 scenario). The additional $CO_2$ emission savings come from the integral production shift towards carbon-neutral power plants (renewables and nuclear).

With a significantly higher $CO_2$ price in the EUCO30-2050 scenario, the difference in variable electricity generation costs between carbon-neutral units and the others is exacerbated. This leads to a higher price spread between peak and off-peak hours, and ultimately to more important production cost savings through smart heat pump operation (cf. Table 5). In addition to this price difference, the flexibility offered by heat pumps in Option B reduces the number of hours where the power demand was not met (loss of load), and thus significantly diminishes the market price during these hours.[25]

In total, the production cost savings sum up to almost 6 bn€/year due to flexible heat pumps with thermal storage. These savings represent around 3% of the whole EU power production costs (excluding loss of load costs).

*Table 5 - Savings under Option B compared to Option A in the EUCO30-2050 scenario*

| | Option B vs option A |
|---|---|
| $CO_2$ emission savings | 3 Mt/y |
| Production cost savings | 5 800 M€/y |
| Production costs saving per $MW_{thermal}$ of smart heat pump | 27 000 €/$MW_{thermal}$/y |

[25] In the METIS power system module, the price of loss of load is set to 15 000 €/MWh.

# 8. IMPACTS OF BIVALENT HEAT PUMPS ON THE POWER SYSTEM (OPTION C VS A)

With a green power mix, heat pumps are a convenient way to decarbonise the space heating sector. However, as explained in Section 6, monoenergetic heat pumps imply negative repercussions on the power system, in particular with respect to intensified power demand peaks during the coldest days, requiring additional peak capacities and potentially a reinforcement of electricity grids. In the most conservative scenario (REF16-2030), the profitability of monoenergetic heat pumps is more than unlikely, while EUCO30-2050 could be a possible environment to reach heat pumps profitability. However, a variant with a more conservative $CO_2$ price of 100 €/t has shown that this profitability is more than uncertain.

The purpose of Option C is to assess an alternative taking advantage of the high efficiency of heat pumps, but with limited power peaks and contained investment costs. In this option, 30% of all heat pumps are considered to be bivalent, that is equipped with a gas boiler back-up heater, in order to decrease power consumption peaks. The sizing of the back-up heater is also different between Option A and Option C, with 60% of heating demand covered by the heat pump (and 40% by the gas back-up heater) instead of a 95%-5% ratio between heat pump and the electric back-up for monoenergetic heat pump systems. This difference of consumption between monoenergetic and bivalent heat pump systems is illustrated in Figure 28.

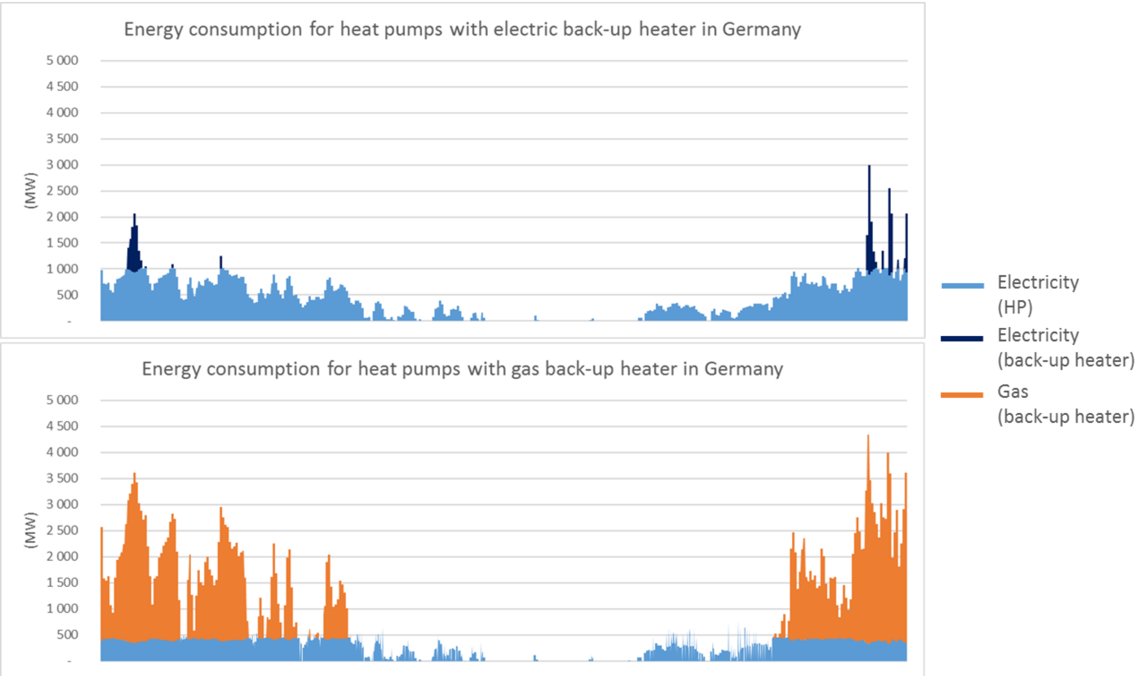


*Figure 28 - Difference in energy consumption between monoenergetic and gas bivalent heat pump systems (Germany, REF16-2030 scenario)*

## 8.1. REF16-2030 SCENARIO

### 8.1.1. *LIMITED $CO_2$ EMISSIONS INCREASE WHEN SHIFTING FROM ELECTRIC TO GAS BACK-UP*

With 30% of bivalent heat pumps across Europe, 10 TWh of the electricity consumption from monoenergetic heat pumps is replaced by 30 TWh of additional gas demand. At the same time, the power generation from gas units is reduced (10 TWh decrease of gas consumption), resulting in a net gas consumption increase of 20 TWh. Given that bivalent heat pumps in Option C are supposed to be equipped with thermal storage, their flexibility leads to a better integration of nuclear and wind (part above 0 in Figure 26). At the same time, power generation from CCGT, coal, OCGT and pumped storage is reduced. The shift from efficiently used electricity towards gas implies 0.4 Mt (0.1%) of additional $CO_2$ emissions between Option C and Option A, despite the shift towards low-carbon electricity generation.

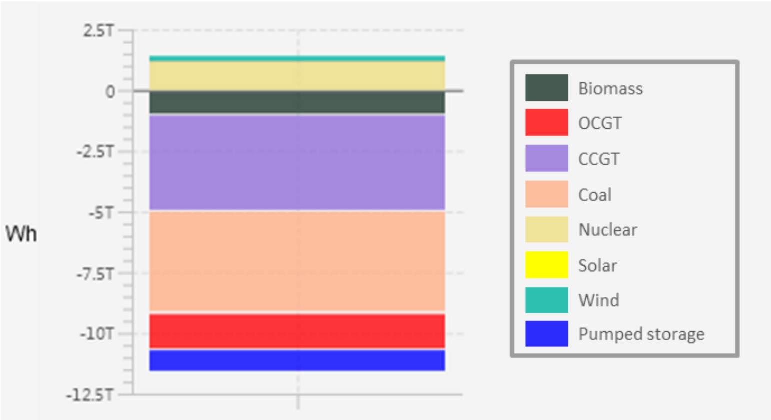


*Figure 29 - Difference of power production for EU between option C and option A in REF16-2030*

### 8.1.2. *PROFITABILITY OF SHIFTING TOWARDS BIVALENT HEAT PUMPS*

The change in the energy consumption and the peak power generation capacities directly imply the profitability of the shift towards bivalent heat pumps. The effects are two-fold:

- Under Option C, operational expenditures are more important compared to Option A. Back-up gas boilers replace electric back-up heaters and heat pumps for heat generation, thereby raising the costs for gas demand (and related $CO_2$ costs), while the savings in power production costs are about 25% smaller (cf. Figure 30). This results in a net increase in operational expenditures of 0.3 bn€/year.
- At the same time, capital expenditures related to investments in OCGT capacities and heat pumps turn out to be lower in Option C compared to Option A, due to reduced consumption peaks and a smaller dimensioning of the heat pump systems. Overall savings sum up to 1.6 bn€/year.

The profitability of bivalent heat pumps versus monoenergetic heat pumps (Option C vs Option A) is almost symmetric with the profitability of monoenergetic heat pumps versus gas boilers (Option A vs Option 0). Thus, the profitability of Option C vs A (cf. Figure 30) is almost the opposite of the profitability of Option A vs 0 (cf. Figure 17).

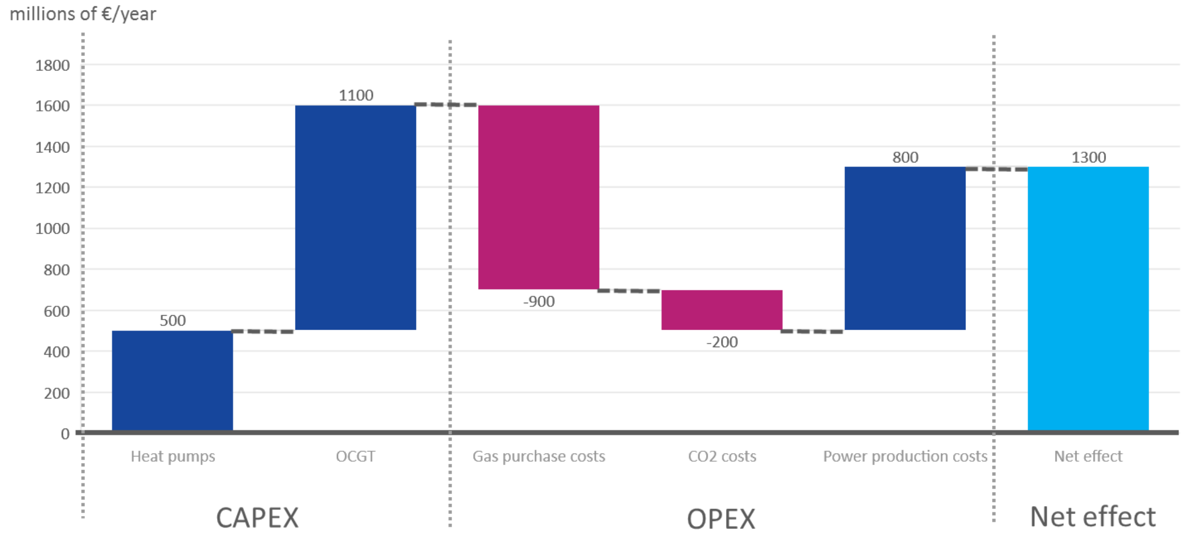


*Figure 30 - Benefits of Option C vs Option A in the REF16-2030 scenario*

According to the previous analysis, bivalent heat pumps appear to be less expensive than monoenergetic heat pumps (in terms of system costs), but accompanied by a limited $CO_2$ emissions increase. Hence, the question arises whether it would be an interesting option to replace conventional gas boilers by bivalent heat pumps, in term of costs and in $CO_2$ emissions (i.e. Option C vs Option 0).

### 8.1.3. Replacing gas boilers by bivalent heat pumps

Option 0 has 47 $GW_{th}$ of gas boilers capacity, while Option C has 30 $GW_{th}$ of heat pumps.[26] In order to compare the two technologies, it is necessary to express the different savings calculated in the previous parts per unit of installed thermal capacity.

*Table 6 - Cost and $CO_2$ savings between Option C and Option 0 (EU level, REF16-2030 scenario)*

| | Savings of Option A vs 0 | Savings of Option C vs A | Savings of Option C vs 0 |
|---|---|---|---|
| Savings per $MW_{th}$ of heat pumps (€ /$MW_{th}$/year) | - 37 000 | 44 000 | 7 000 |
| $CO_2$ emissions reduction per $MW_{th}$ of heat pumps ($t_{CO2}$ /$MW_{th}$/year) | 150 | - 10 | 140 |

When expressed per thermal installed capacity, it is possible to sum the savings of Option A vs 0 and Option C vs A to obtain the saving of Option C vs 0, thereby comparing bivalent heat pumps with gas boilers.

In the REF16-2030 scenario, heat pumps with gas back-up heater appear to be a cost-effective solution to replace conventional gas boilers, with 7 000 €/$MW_{th}$/year of savings from a system perspective (cf. Table 6). It is important to keep in mind that this profitability

[26] The installed capacity of gas boilers in Option 0 for scenario REF16-2030 is the difference of HP installed capacity between 2015 and REF16-2030 in The electricity consumption of heat pumps is finally used to calibrate the METIS heat pump model. We assume that in the European Commission scenarios, all heat pumps are monoenergetic, with the characteristics defined in Section 4.2.. In Option C, the installed capacity of heat pumps is equal to 30% of the whole EU heat pump capacity in Option A, i.e. 30% × 101 $GW_{th}$ = 30 $GW_{th}$.

analysis relies a lot on the different cost hypotheses (investment costs, gas and $CO_2$ price evolutions), and the conclusion could change with different future evolutions.

Contrasting the 140 $t_{CO2}/MW_{th}$/year of $CO_2$ emission savings from bivalent heat pumps with the 150 $t_{CO2}/MW_{th}$/year emission savings from monoenergetic heat pumps reveals that both solutions are relatively close in terms of emission reduction, but Option C features an economic advantage. Yet, this result is strongly driven by the assumption on the 40% gas and 60% heat pump contribution in the bivalent heat pump. In the end, the result describes the trade-off between low emissions and low costs. This trade-off diminishes with rising $CO_2$ prices. It is thus to be concluded that the adequate calibration of bivalent heat pumps depends on the carbon content of power and the price spread between electricity and gas, which is strongly influenced by the $CO_2$ price (cf. next section).

## 8.2. EUCO30-2050 SCENARIO

### 8.2.1. *LIMITED $CO_2$ EMISSIONS INCREASE WHEN SHIFTING FROM ELECTRIC TO GAS BACK-UP*

Similar to the REF16-2030 scenario, the 30% of bivalent heat pumps result in a lower power demand (-11 TWh) and a shift in the power production (as shown in Figure 31). The electricity consumption from monoenergetic heat pumps is replaced by 65 TWh of additional gas demand. At the same time, the power generation from gas units is reduced (40 TWh decrease of gas consumption), resulting in a net gas consumption increase of 25 TWh.The power production decrease mainly applies to mid-merit units and peakers (CCGT and OCGT), due to their comparatively high variable generation costs. Instead, the flexibility offered by the thermal storage of the bivalent heat pumps favours a better integration of renewable and nuclear production.

The shift from efficiently used electricity towards gas implies 2.5 Mt (1%) of additional $CO_2$ emissions between Option C and Option A. It is a higher increase than in REF16-2030 scenario (0.1%), because the power mix in EUCO30-2050 is more decarbonised (hardly any coal left in the power mix) than in REF16-2030. Thus, reducing the power production between Option C and Option A leads to less important $CO_2$ emissions reduction than in REF16-2030 scenario.

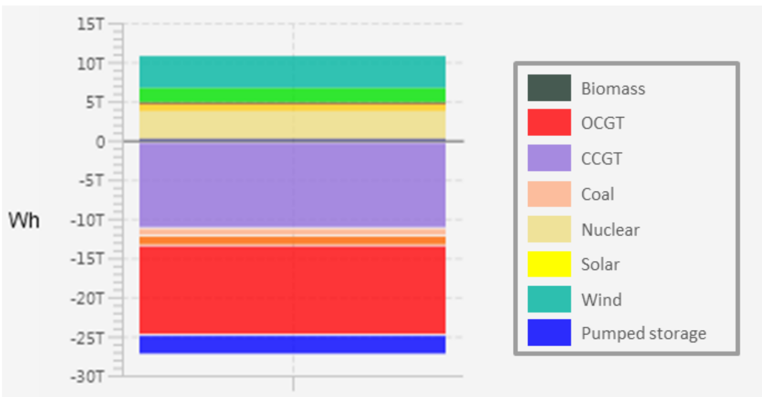


*Figure 31 - Difference in power production for EU between option C and option A in the EUCO30-2050*

### 8.2.2. *PROFITABILITY OF SHIFTING TOWARDS BIVALENT HEAT PUMPS*

Similar to the REF16-2030 scenario, the partial shift towards bivalent heat pumps is profitable from a system perspective. The main reasons of the profitability of bivalent heat pumps vs monoenergetic heat pumps are the important savings coming from the lower power production costs, the important reduction of loss of load costs and the important reduction of OCGT investments[27] (cf. Figure 32).

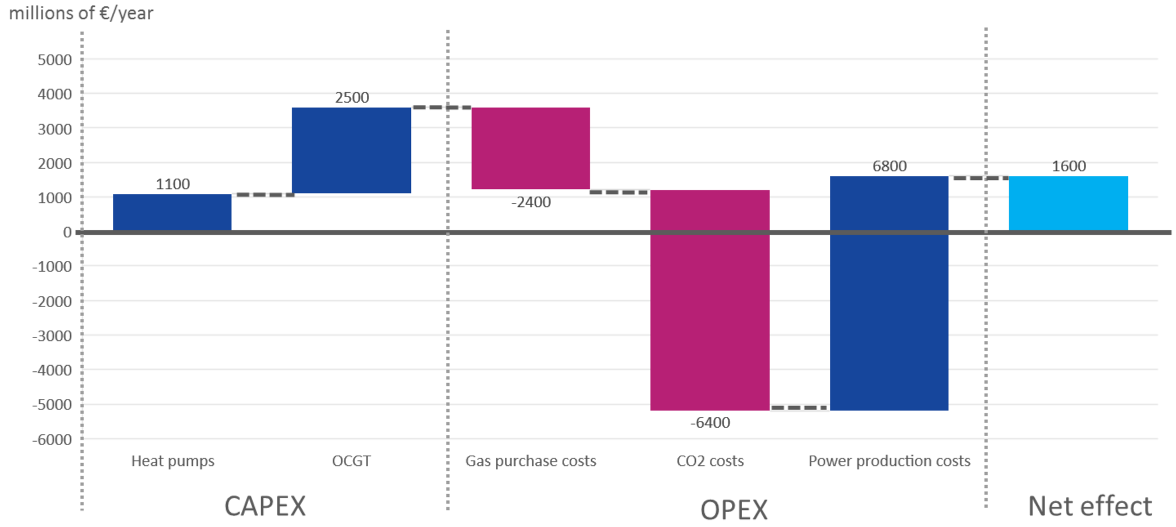


*Figure 32 - Benefits of Option C vs Option A in the EUCO30-2050 scenario*

**Replacing gas boilers by bivalent heat pumps**

Similar to the REF16-2030 scenario, the increase in emissions under Option C compared to Option A triggers the question, whether it is efficient to shift towards bivalent heat pumps in comparison with gas boilers (Option 0). While replacing gas boilers by bivalent heat pumps is an interesting solution to benefit from the high efficiency of heat pumps with limited investment costs in the REF16-2030 scenario, the alternative does not appear to be crucial for the EUCO30-2050 scenario since monoenergetic HPs are already profitable over gas boilers (cf. Section 6.2.3 and Table 7).

However, since bivalent heat pumps are more profitable than monoenergetic heat pumps, it is still possible to replace gas boilers by bivalent heat pumps. The savings would be more important than with monoenergetic heat pumps[28] (143 000 instead of 116 000 €/$MW_{th}$/year), but the $CO_2$ emissions reduction would be slightly lower (250 instead of 290 t/$MW_{th}$/year).

*Table 7 - Cost and $CO_2$ savings between Option C and Option 0 (EU level, EUCO30-2050 scenario)*

| | Savings of Option A vs 0 | Savings of Option C vs A | Savings of Option C vs 0 |
|---|---|---|---|
| Savings per $MW_{th}$ of heat pumps (€ /$MW_{th}$/year) | 116 000 | 27 000 | 143 000 |
| $CO_2$ emissions reduction per $MW_{th}$ of heat pumps ($t_{CO2}$ /$MW_{th}$/year) | 290 | - 40 | 250 |

[27] One should note, that Option C includes heat pumps with thermal storage, whose influence leads to a better integration of RES and nuclear, and thereby to lower power production costs. The reduction in loss of load could is either related to the lower demand peak resulting from fewer electric back-up heaters, or to the flexibility offered by heat pumps' thermal storage. That is, the profitability of bivalent heat pumps vs monoenergetic heat pumps is probably lower when excluding the benefits of thermal storage.

[28] Cost calculations do not include electricity or gas infrastructure costs.

# 9. CONCLUSION

This study has as objective to determine the benefits of decentralised heat pumps for the European energy system, considering different technical configurations, at the time horizon 2030 and 2050. For this purpose, the EU energy system model METIS was further extended in order to adequately simulate the hourly behaviour of the heat pump power consumption considering national ambient temperature time series, and assess the potential flexibility associated with heat storage or gas back-up.

The assessments reveal that decentralised heat pumps in the residential and tertiary sectors may significantly reduce carbon emissions compared to decentralised boilers using gas (or even more carbon-intensive fuels). This is primarily due to the high efficiency of heat pumps. In the 2030 scenario, this reduction is rather limited (1%), because the additional heat pumps' electricity consumption is partially generated from fossil-fuelled power plants. However, in the 2050 scenario, the higher carbon price and the additional renewable power generation capacities drive down the carbon content of electricity. Combined with a larger penetration of heat pump systems (twice the capacity of the 2030 scenario), this leads to nearly 20% $CO_2$ emissions reduction.

However, the shift towards heat pumps translates into rising power demand and rising demand peaks, that occur in particular in winter times, when the levels of electricity consumption in most European countries already reach their annual highs. That is, a further rise in demand peaks requires additional peak capacities and raises network costs.

Two potential mitigation strategies are tested in this study and proved effective. Equipping heat pumps with a distinct thermal storage (that allows to buffer two-hour heat output at full capacity) and operating them in a smart manner (assuming that a time-varying tariff reflects situations of peak demand or network stress) helps to avoid the coincidence of heat pump electricity consumption with the daily demand peak. Further, running the heat pump in a bivalent mode with a gas boiler as back-up allows switching to gas when the annual demand peaks occur, and thus prevents a further amplification.

Yet, with carbon prices below 50 €/t$CO_2$, the installation of purely power-based (i.e. monoenergetic) heat pump systems is not competitive from a system perspective as it requires the simultaneous investment in peak power generation units. In contrast, bivalent systems with gas back-up are competitive but feature a slightly lower emission reduction (-7%). As soon as the $CO_2$ price is sufficiently high (>100 €/t), both monoenergetic and bivalent heat pumps are competitive and the choice is motivated by a trade-off between cost and $CO_2$ emissions.

The study results prepare the ground for further analyses.

The impact assessment realised with respect to demand peaks and power plant dispatch could be further extended by co-optimising heat pump roll-out and the adequate expansion of power generation capacities. Adding the dimension of distribution and transportation grids to the analysis would enable an even more holistic assessment, considering potential implications with respect to resulting grid bottlenecks and situations of network stress. Such assessments are foreseen in the METIS 2 project.

Given the restricted contribution of short term heat storages to prevent an increase in the annual demand peaks, storage facilities with higher capacity could represent a more promising solution to reduce the need for gas back-up, further facilitate RES integration and benefit from larger price spreads.

The carbon footprint of the gas back-up heater could be compensated via the utilisation of synthetic methane, generated via a Power-to-gas process. This would in turn affect the cost-effectiveness of this solution. METIS Study S1 determines the cost-optimal ratio between gas and electric back-up on a country by country basis assuming that all gas is originates from Power-to-gas.

Finally, the quantification of potential savings related to the smart and flexible operation of heat pumps could be extended to other market segments (such as reserve markets) in order to fully capture all related system benefits.

# 10. REFERENCES


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# 11. APPENDIX

## 11.1. DIFFERENCE OF $CO_2$ EMISSIONS BETWEEN OPTION A AND OPTION 0

Difference of $CO_2$ emissions between Option A and Option 0 (only from power production, excluding gas boilers)

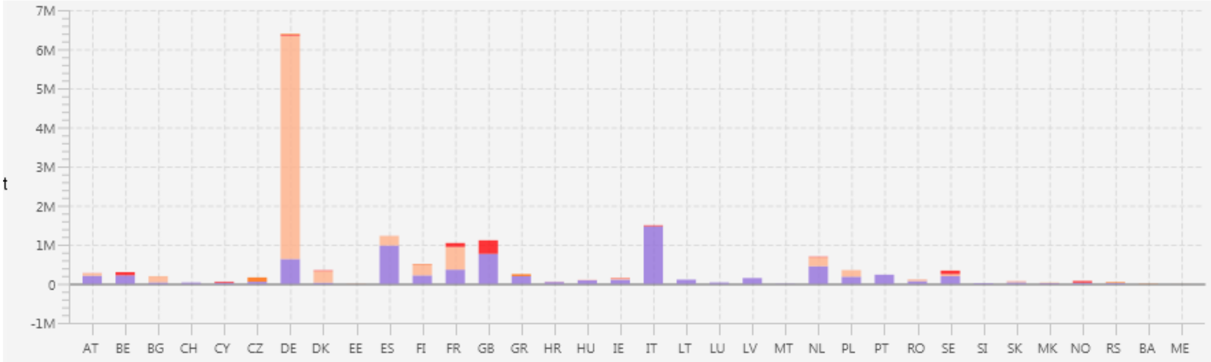


*Figure 33 - Difference of CO2 emissions between option A and option 0, in scenario REF16-2030*

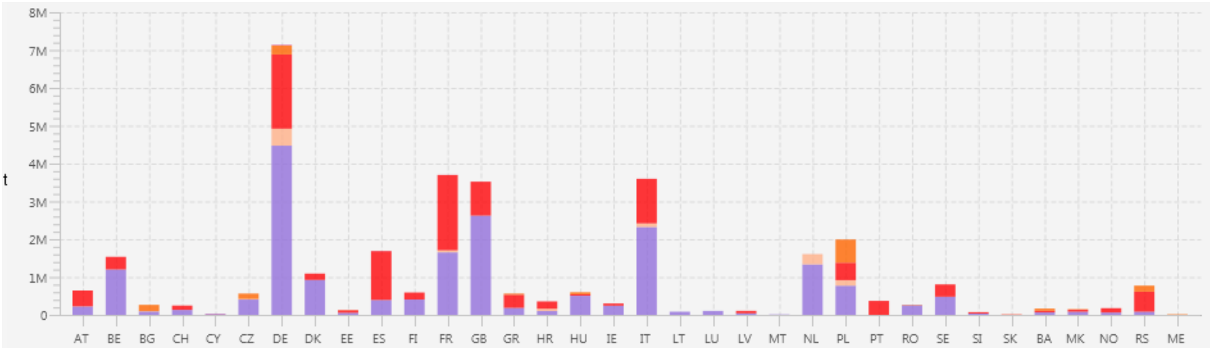


*Figure 34 - Difference of CO2 emissions between option A and option 0, in scenario EUCO30-2050*

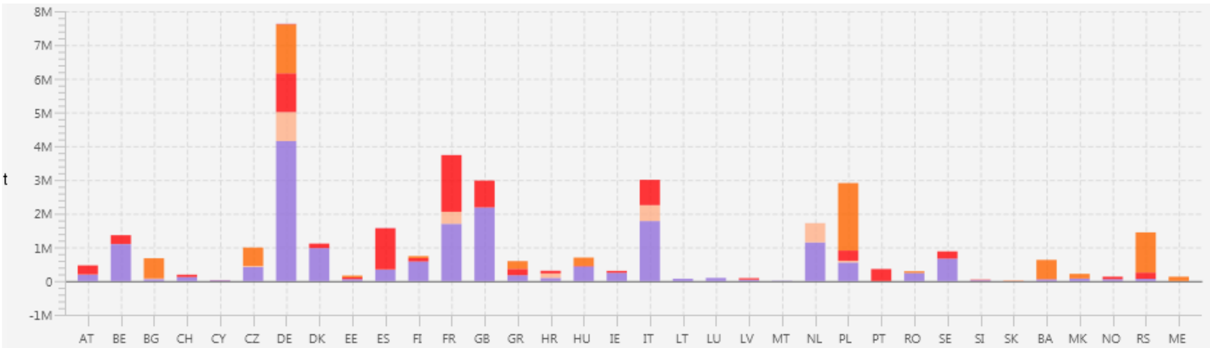


*Figure 35 - Difference of CO2 emissions between option A and option 0, in scenario 2050-Variant*

## 11.2. Difference of power production between Option B and Option A

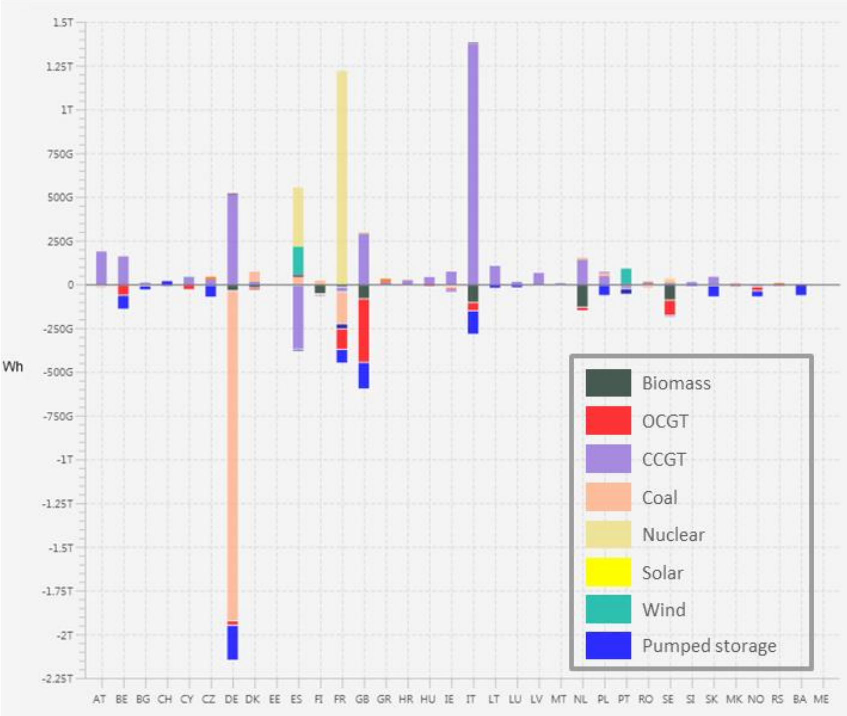


*Figure 36 - Difference of production between Option B and Option A, in Scenario REF16-2030*

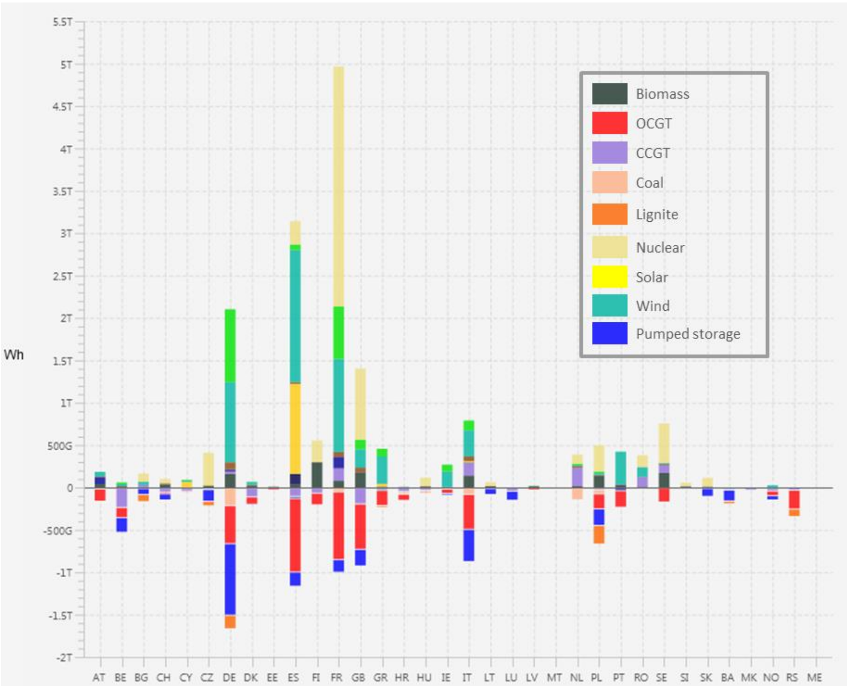


*Figure 37 - Difference of production between Option B and Option A, in Scenario EUCO30-2050*

## 11.3. NUMBER OF LOSS OF LOAD HOURS

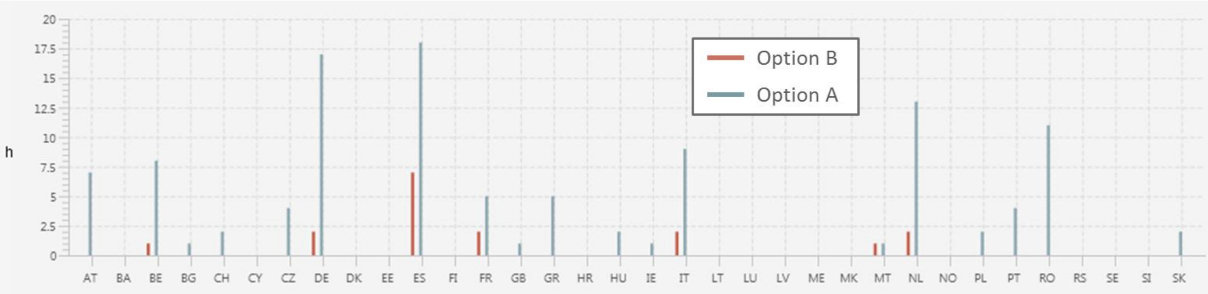


*Figure 38 - Number of hours where the power demand was not met (loss of load) in Scenario EUCO30-2050*

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