The PENTAGON project is co-funded by the EU's Horizon 2020 programme under grant agreement No. 731125

UNLOCKING EUROPEAN GRID LOCAL FLEXIBILITY THROUGH AUGMENTED ENERGY CONVERSION CAPABILITIES AT DISTRICT-LEVEL

DELIVERABLE 2.5: POWER-TO-HEAT TECHNOLOGY INTEGRATION STRATEGIES

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**Deliverable Administration & Summary**

**D3.1 Power-to-heat technology integration strategies**  
Lead Beneficiary: Tractebel

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**Document change history**

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<th>Date</th>
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<td>Michael Descamps (CEA), Mathieu Vallée (CEA), Ramprakash Puri (EXE), Johannes Düll (EXE), François Promel (TRA)</td>
<td>Delivery of the requested contributions by the project partners involved</td>
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<tr>
<td>16/11/2017</td>
<td>Michael Descamps (CEA), Ramprakash Puri (EXE), Johannes Düll (EXE)</td>
<td>Integration of all the comments and updates, resulting in a consolidated version.</td>
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EXECUTIVE SUMMARY

In this deliverable, a critical assessment of Power-To-Heat (P2H) technologies is carried out.

Commonly used P2H technologies are reviewed, with an overview of their typical characteristics and some relevant examples of use at district or building level. A comparison of the technologies considered shows that heat pumps are more cost efficient in the long term than electric resistance technologies, particularly for large scale developments. Until recently, heat pumps have been mainly used as a base load technology, as opposed to electric boilers and domestic hot water (DHW) tanks which are historically more suited for peak load and flexibility purposes, however technological innovations applied to heat pumps are challenging this status quo.

An analysis of European clustering shows that there are strong geographical variations in the use of P2H, which can be explained by the variety of climates, local resources, national policies and energy prices, among others. As a general trend, air to air heat pumps are used for cooling purposes in Southern Europe, whereas water/ground to water heat pumps are used in Northern/Eastern Europe for space heating and hot water. In terms of performances, the coefficient of performance (COP) of heat pumps is influenced by the temperature of the source, which itself depends on the local climate. In contrast, electric resistance technologies are not clustered by climatic zones. A focus on 5 countries or geographical zones (Italy, Eastern Europe, Sweden, Germany, France) illustrates the variability in P2H technologies.

Finally, a set of P2H technologies is recommended for the eco-districts of interest in the PENTAGON project, as described in D3.1. Depending on the resources available in the vicinity of the eco-district, a water to water or ground to water heat pump is proposed to provide the base heat load for the district. However, it should be noted that the optimal combination of P2H technologies is closely tied to an adequate set of storage capability. This aspect is not covered in this deliverable.

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<td>Air sourced heat pump</td>
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<td>CAPEX</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<td>District heating</td>
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<td>WSHP</td>
<td>Water sourced heat pump</td>
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1 INTRODUCTION

1.1 AIMS AND OBJECTIVES

The objective of this deliverable is to review district and building-level power-to-heat (P2H) technologies, in order to assess the best strategies for upgrading building district capacities to effectively act as leverage. Power-to-Heat technologies include all electrical heating / cooling production devices, as well as heating / cooling storage devices: heat pumps, air-conditioning, electrical boilers, hot water tanks, etc. The assessment will include three phases:

1. Individual assessment and ranking of technologies based on efficiency and cost;
2. Clustering based on European climatic zones and building typologies;
3. Assessment of optimal combination of technologies on a restricted set of eco-district configurations.

1.2 RELATIONS TO OTHER ACTIVITIES IN THE PROJECT

The work described in this deliverable is an input to T 2.6 (Detailed specifications of selected energy conversion technologies). The detail specifications will then support the development of the building and district level simulation and prediction environment in WP3 (Multi-scale, multi-vector flexibility management platform).

1.3 REPORT STRUCTURE

In section 2 a selection of commonly used power-to-heat technologies are presented and compared, both qualitatively and quantitatively. Section 3 focuses on the clustering of technologies, looking at the influence of the geographical distribution of resources and the climatic zones. The main takes from sections 2 and 3 are summarised in section 4, which presents some elements of decision in the choice of P2H with suggested application to the typical eco-district identified in D3.1.
2 ASSESSMENT OF POWER-TO-HEAT TECHNOLOGIES

Power-to-heat (also referred to as electricity-to-thermal or power-to-thermal by some authors) refers to technologies that convert electricity into thermal energy, either for cooling or heating purposes. Power-to-heat can add flexibility to a power system, by converting excess renewable electricity into heat [1]. The benefits of such a strategy are twofold: first, the demand for thermal energy usually dominates the final energy use, and second, it is easier to store thermal energy than electricity. It is worth mentioning that with P2H, most attempts have focused on identifying its potential for district heating purposes and/or as a part of virtual power plant. For example, in Germany, it was found that the technical potential of P2H in district heating grids accounts for 6 GW in 2015 and 20 GW in 2030 [2].

P2H technologies are mainly based on thermodynamic cycles or on the Joule effect. Thermodynamic cycle technologies make use of an external source of energy (e.g. body of water, outdoor air etc..) and electricity to run a compressor and the pumps. Examples of P2H technology based on thermodynamic cycle include heat pumps and absorption chillers. Joule effect technologies are based on the principle of resistive heating. Some examples include domestic hot water tanks or electric heaters.

In the following, a selection of P2H technologies are reviewed with respect to their technology and their different levels of focus: district, building, or household. The results are then summarised in section 2.5.

2.1 HEAT PUMPS AND THERMODYNAMIC HOT WATER SYSTEMS

With a coefficient of performance in the typical range 3 to 6, heat pumps are energy efficient devices, compared to combustion based heating systems [3]. The origin of the energy source can be natural, or can come from waste energy, making heat pump possibly the only technology that recirculates environmental and waste heat back into a heat production process; offering environmentally friendly heating and cooling in applications ranging from domestic and commercial buildings to process industries [4]. Recent practical arch studies have shown the potential of heat pumps to significantly reduce greenhouse gases, in particular CO2 emissions, in space heating and heat generation. Furthermore a 2009 EU legislation recognizes heat pump technology as necessary to make use of renewable energy sources [5]. The positive impact on environment predominantly depends on three factors: the type of heat pump, the energy-mix and efficiency of driving power used.

The general operating principle of a heat pump is shown in Figure 1.
The heat is distributed by a hydronic distribution system or by air. Hydronic distribution systems are used for space heating/cooling and domestic hot water (DHW). The water circuit is connected to a network of radiators or an under-floor heating system, with possibly a water tank acting as thermal storage. Air distribution systems are commonly used for space cooling and space heating to a lesser extent.

Heat pumps differ in many respects from conventional oil heating and direct electrical heating. With an oil burner, a heat pump is a central heating system, in other words, heat is transferred to the rooms by water or air. If the heat pump is electrically operated, but it needs only a small proportion of that of a direct electric heating.

In the following sections, some commonly used heat pumps are presented and classified by heat source. The **Coefficient of performance (COP)** is defined as follows [7]: the amount of heat the heat pump produces compared to the total amount of electricity needed to run it. The higher the COP, the less electrical energy is required to deliver a given amount of heat: a high COP shows good performance, and a low COP shows poor performance.

### 2.1.1 WATER SOURCED HEAT PUMPS

Water sourced heat pumps (WSHP) have a high efficiency compared to air sourced heat pumps, since the heat transfer coefficient on the heat exchanger is higher for water than for air, making water a better energy carrier. Any body of water, e.g. river, see, lake, underground aquifer can be seen as a storage of low grade heat that can be replenished [8]. In addition, sewage water, representing waste water from human activity, can be used as heat source [9].

The heat extraction process is optimal for a constant temperature of the water source throughout the year, as the heat pump then operates at a constant COP. In practice, the water intake is located at a depth of the water body that guarantees this condition. Ambient water temperature can vary between 2 to 14°C depending on the season. On the other hand, sewage water allows for a more efficient heat recovery as its temperature varies in the range 12 to 20°C.

In terms of distribution fluid, WSHP can be either water-to-air or water-to-water heat pumps. Water-to-water heat pumps can be used for space heating/cooling and DHW. Heating/cooling changeover can be done in the refrigerant circuit, but it is often more convenient to perform the switching in the water circuits. Several water-to-water heat pumps can be grouped together to create a central cooling...
and heating plant to serve several air handling units. This application has advantages for better control, centralized maintenance, redundancy, and flexibility.

At household and building levels, WSHP’s are mainly based on underground aquifers or rivers as a primary heat source. The thermal power generated is found in the range 7 to 140 kW for different manufacturers. Depending on the local legislations, various administrative authorizations are needed to drill holes in the ground or to install an intake in a river [10]. Adding to the relatively high investment cost of the heat pump itself, this configuration is not widespread at household level.

At district level, WSHP’s are used for district heating and domestic hot water. Using a larger share of the renewable energy resource, the technology is more efficient at this level and can help stabilizing the city’s energy demand. Historically limited to Scandinavia, Switzerland and Japan, large scale WSHP’s with thermal power in the range 1-13 MW, are gradually being deployed in other European countries, following national and European policies to diversify away from fossil fuel dependency [8]. The usual ambient heat sources are rivers, sea and lakes, so this configuration is well suited for districts in the vicinity of urban rivers or estuaries. Using sewage water a heat source removes this dependence on a natural body of water. In Sweden, the heat capacity from sewage water is twice that of ambient water [9]. In [11], a study on a district heating network in France showed that using a WSHP was cost efficient for the base load, where as it was not the case for peak load.

A large scale example is the Drammen District Heating in Norway [12] that serves over 200 large buildings. A heat pump draws water from the fjord at 8C and cools it down to 4C, delivering 13 MW of heating power through a hot water circuit at a temperature of 90C. Using ammonia as a working fluid, the COP is 3.05 at 90 C.

A smaller scale example is the Kingston Heights Development in West London; where 2MW of low grade energy is extracted from the Thames River by a set of 41 WSHP’s with COP in the range 4 to 6 [13]. The heat is delivered to 137 households and a 145 bedroom hotel in the form of space heating and DHW.

2.1.2 GROUND SOURCED HEAT PUMPS

Ground sourced heat pumps (GSHP) present some similarities with WSHP’s, in that the energy is extracted from a large body at constant temperature, in this case the ground. GSHP’s are used in the case of shallow geothermal energy, for which the heat energy stored in the near surface layers comes predominantly from the Sun. For deeper geothermal reservoirs for which the temperatures reach 100 C, the energy can be directly transferred to the district heating network using subsurface heat exchangers, without the need for GSHP’s [14].

Heat is extracted by cycling an alcohol and water mixture through a set of horizontal, vertical, or coiled pipes embedded in the ground, typically 1 m below the ground surface for horizontal collectors, and up to 80 m below the ground surface for vertical collectors. Horizontal collectors are cheaper to install but require an area which is typically twice that of the heating area [10], so these collectors are more common for houses with gardens. The constraints on the area surrounding a building means that in general, GSHP’s are more suited to new buildings for which the collectors are included in the early design phase.

GSHP’s may work as a direct exchange system or via a secondary loop. In a GSHP using a direct exchange system, the refrigerant exchanges heat directly with the soil through the copper tubing without any intermediary. By contrast, the other type of GSHP’s rely on primary refrigerant loop that exchanges heat with a secondary ground loop containing a mixture of water and anti-freeze.

Through the soil the solution warms approximately by about 2-3 degrees. In principle, the same technique can also be applied to extract the heat from the bottom of the lake, for example, where the tube is anchored with appropriate weights.
GSHP’s are effective systems for space heating and cooling, but have a high investment cost due to the need to bury heat exchangers underground and drill wells for heat sourcing. However, their running costs are lower [3]. In [15] an analysis of various combination of HP shows that combining a combined heat and power (CHP) unit and a GSHP allows to increase the penetration levels of VRE source.

GSHP’s are more common at household and building levels.

An example of GSHP use is the renovation of the historic Soutlon Hall in Shropshire, UK [16]. Two GSHP’s with a total output of 62 kW provide space heating and domestic hot water to a 30-room manor house and a coach house. The horizontal collector was laid over an area of 3 acres (12140 m²).

2.1.3 AIR SOURCED HEAT PUMPS

As a domestic heating technology, air source heat pumps (ASHP) can be considered a very cost effective option for heating residential premises in particular, areas with no gas access. They are primarily used for space cooling of single rooms and entire buildings, with air as the secondary circuit fluid (air-to-air heat pumps). The usual ASHP’s for air conditioning are reversible and can be used for space heating as well, making them a cost effective options when both space heating and cooling are required throughout the year [3]. ASHP’s with water as a secondary circuit fluid (air-to-water HP) are commonly used for space heating.

Compared to ground sourced and water sourced heat pumps, ASHP’s have lower performance ratios, but have the advantage of being easier to install because neither underground nor water equipment is needed, which also makes them cheaper and suitable for mass production in factories. Furthermore, they are well suited for the renovation sector [17].

At household levels, the typical performance of air-to-air heat pumps used for air-conditioning and space heating can be found using the Energy Star certification database [18]. The values for Energy Efficiency Ratio (EER), Seasonal Energy Efficiency Ratio (SEER), and Heat Seasonal Performance Factor (HSPF) are converted to a COP in Figure 2. It can be seen air-to-air heat pumps have a COP in the range 3 to 4 in heating mode. The typical thermal power at household level is in the range 1-10 kW.

![Figure 2: Coefficient of Performance of ASHP based on Energy Star Most efficient 2017 models available for sale in the US and Canada [18]](image)

An economic analysis considering Ireland, estimates that by using ASHP technology, 60% of homes using oil have the potential to deliver savings in the region of €600 per annum when considering both
running and annualised capital costs [19]. In another study at household level, using ASHP’s was shown to increase the thermal comfort, lower the heating costs, improved the controllability of heating and increased the automation compared to storage or solid fuel [20].

At building level, ASHP’s can provide thermal power in the range 7-150 kW, for a COP of 3–4, though the COP of highly–efficient ASHP’s can be higher than 6. Air-to-water heat pumps can be used for space heating/cooling and domestic hot water of larger buildings. Water tanks of 200 to 800 L are optionally included by some manufacturers for thermal storage [21].

A representative example at district level is the Glasgow Housing Association project, which will see 350 homes in multi–storey which will benefit from an ASHP for heating and DHW [22]. The heat pump is of air-to-water type with a power of 700 kW and a COP of 3.

### 2.1.4 HIGH TEMPERATURE HEAT PUMPS

The term ‘high temperature heat pump’ either refers to heat pumps which use heat sources at higher temperature levels and therefore deliver higher temperatures or to heat pumps which work with two Rankine cycles in cascade, which this way can deliver higher temperature levels.

In [23] a literature review of the state of the art of high temperature heat pumps in the first mentioned sense is undertaken. These heat pumps use heat sources at 20°C on up to 90°C and convert them into heat at 80-165°C. Especially in industry, a high potential for this type of heat pumps is seen as waste heat often is produced at temperatures between 20 and 60°C [23] but it also might be interesting in the context of the PENTAGON project and district heating networks/ P2H. Table 1 gives an overview of available models in the market, specifying the power range and temperature level they can deliver.

<table>
<thead>
<tr>
<th>Manufacturer</th>
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<th>Temperature level [°C]</th>
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<td>Kobelco (Steam Grow Heat Pumps)</td>
<td>SGH 165</td>
<td>165</td>
<td>70-660 kW</td>
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<tr>
<td></td>
<td>SGH 120</td>
<td>120</td>
<td>70-370 kW</td>
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<td></td>
<td>HEM-HR90, HEM-90A</td>
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<td>70-230 kW</td>
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<td>Hybrid Energy</td>
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<td>120</td>
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<td>Viessmann</td>
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2.1.5 THERMODYNAMIC HOT WATER TANKS

Thermodynamic hot water systems, also called heat pump water heaters, are a subset of heat pump systems designed specifically for DHW at household level. They are categorised as air to water heat pump, where the distributed water is used as DHW. The COP is typically in the order of 2-3 [11], which is quite low for a heat pump, however these systems include thermal storage in the form of a tank of 200 to 500L. Furthermore, thermodynamic hot water tanks can also work as conventional DHW tanks (presented hereafter in section 2.2) with an electrical resistance, which guarantees the production of DHW even when the ambient air temperature is too low.

2.2 DOMESTIC HOT WATER TANKS

Domestic hot water tanks are the historical power-to-heat conversion technology before the rise of thermodynamic machines. Assuming a perfect conversion efficiency of the Joule effect, all the electric energy feeding a DHW tank is converted to heat, which represents a COP of 1 at most. While the performance of a DHW tank is lower than that of a heat pump, the investment cost is much lower, making it a more practical solution when only domestic hot water is needed.

DHW tanks also include thermal storage, which can add flexibility to the electricity demand. For instance, in France, 12 million households are equipped with DHW tanks, and 10% of household energy consumption is devoted to DHW, which represents a significant part of the electric consumption at the national level [11]. Thanks to a relatively short charging time, flexibility can be leveraged by charging the tanks at night, or during a peak in production of variable renewable energy. In [24], a model predictive control (MPC) strategy for scheduling the consumption of a DHW tank according to the forecasted PV production is compared to a traditional control strategy by a thermostatic controller. The MPC strategy leads to a maximisation of PV self-consumption, and a reduction of the energy bill reduction of 15% over a day. Scaling such results to a district means that the scheduling of household appliances has to be considered, which is beyond the scope of this report.

In terms of specifications, DHW tanks usually have a power in the range 0.5 to 2 kW for a volume of 50 to 500 L at household level, whereas at building level, the power can range up to 30 kW for a volume up to 6000 L.

2.3 ELECTRIC BOILERS

Electric boilers are used for producing hot water directly from electricity. The heat can be generated from an electrical resistance, with a heating power up to 1 MW for small applications, or from electrodes in which case the heating power is in the range 1-25 MW.

Similarly to DHW tanks, electric boilers are seen as a way to improve flexibility, by discharging immediately or within a few hours’ notice. At district level, electric boiler can be associated to a thermal storage, giving the same advantages as DHW tanks.

In [25], a representative configuration consisting of a 5 MW electric boiler associated to a 5000 m³ thermal storage is analysed in the context of Nordic electricity market. The annual heat delivered to customers is assumed to be 64 GWh which, to put in perspective, is roughly equivalent to the heat delivered to the 200 large buildings in the Drammen District Heating example of section 2.1.1. For the scenarios considered, the heat boiler contributes between 3% and 17% of the annual heat supply, mainly concentrated in the summer months, where the electricity prices are low. It is shown that both the level and the short-term variation of the electricity price are decisive factors for the operation of electric boilers in district heating systems, but that overall, electric boilers benefit from variability in electricity price.
2.4 ELECTRIC HEATER, Q-RAD

Electric heaters are included in the Joule effect technologies, since they are based on an electric resistor converting the electricity into heat. These heaters are mainly used at household level, with a typical power in the range 0.2 to 2 kW. Various spaced heating methods are available. The most commonly found is convection heating, whereby a natural convection of air is created in the room by buoyancy effects between cool air and hot air. Fan heating uses forced convection by a fan, which is more efficient than purely by natural convection, but generates noise and is therefore not usually chosen as the main source of heating. Radiative heating uses the infra-red radiations emitted by a bulb to heat people and objects through a reflector. A special kind of radiative heater is the Q.rad heater, which uses microprocessors as a heat source. Q.rad operators propose to recycle the heat generated by workload processing for space heating through a distributed infrastructure [26]. Computing heaters embedding microprocessors as a heat source are deployed in chosen adapted site, such as offices, residence, industries etc.. This ensures that the Q.rad operators can keep a minimum commuting capacity all year long, without having to use any cooling system. As part of this business model, the electricity costs are not beared by the end consumer.

2.5 QUALITATIVE AND QUANTITATIVE COMPARISON

In Table 2 some representative figures are presented on common power to heat technologies. The content of the table comes from a survey based on manufacturers’ catalogues and information available on the internet, and is not meant to be exhaustive, but rather to give some order of magnitudes.

The equipment costs for heat pumps associated to large developments are not publicly available so they do not appear in Table 2.

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<th>Effective electricity cost [€/kWth]</th>
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<td>500-13200</td>
<td>3.55</td>
<td>1732</td>
<td>0.034</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Large Air2Water HP</td>
<td>400-700</td>
<td>3.00</td>
<td>4028</td>
<td>0.040</td>
<td>Y</td>
</tr>
<tr>
<td>Building</td>
<td>Air2Air HP</td>
<td>7-150</td>
<td>3.68</td>
<td>274</td>
<td>0.035</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Air2Water HP</td>
<td>36-530</td>
<td>3.38</td>
<td>635</td>
<td>0.036</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Ground2Water HP</td>
<td>13-35</td>
<td>4.65</td>
<td>616</td>
<td>0.028</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Water2Water HP</td>
<td>17-150</td>
<td>4.90</td>
<td>478</td>
<td>0.025</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Electric boiler</td>
<td>12-35</td>
<td>1.00</td>
<td>226</td>
<td>0.120</td>
<td>N</td>
</tr>
<tr>
<td>Household</td>
<td>Small Air2Air HP</td>
<td>1-10</td>
<td>3.13</td>
<td>885</td>
<td>0.074</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Small Air2Water HP</td>
<td>4-16</td>
<td>4.70</td>
<td>591</td>
<td>0.047</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Small Ground2Water HP</td>
<td>14</td>
<td>4.77</td>
<td>839</td>
<td>0.046</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Electric convector</td>
<td>0.2-1.2</td>
<td>1.00</td>
<td>250</td>
<td>0.220</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Electric heating floor</td>
<td>0.07-1.5</td>
<td>1.00</td>
<td>60</td>
<td>0.220</td>
<td>N</td>
</tr>
<tr>
<td></td>
<td>Small Electric boiler</td>
<td>1-27</td>
<td>1.00</td>
<td>52</td>
<td>0.220</td>
<td>Y</td>
</tr>
<tr>
<td></td>
<td>Small Electric DHW Tank</td>
<td>0.5-2</td>
<td>1.00</td>
<td>151</td>
<td>0.220</td>
<td>Y</td>
</tr>
</tbody>
</table>

From a qualitative point of view, GSHP’s and WSHP’s offer more options as to how the heat is used: for domestic hot water, heating or cooling, although the main usage remains heating. On the other
hand, Joule effect technologies are not reversible and only used for domestic hot water or space heating.

The European Heat Pump Association points out that HP’s can bridge demand and supply patterns between electricity and thermal grids [27]. This approach is leveraged by the thermal storage, which can take the form of the HP hydronic storage, a phase change material, and the thermal mass of buildings. A HP system can then be used as a thermal battery, storing excess electricity into heat, and being able to withstand a few hours of electricity supply interruption. In [27], it is also noted that in cooling mode, heat pumps combined to decentralised photovoltaics can reduce demand peaks and prevent grid overload. However there are still some limitations related to the connectivity, i.e. integrating the heat pump into the building information infrastructure, and enabling exchange of information and remote control of this system by the energy operator. It has also been seen that WSHP’s and GSHP’s are not suitable for the renovation sector, unlike ASHP’s. However in this case the main usage is for cooling.

As far as DHW tanks are concerned, they are currently more likely to benefit from smart tariffs than heat pumps. Furthermore, as pointed out in section 2.2. The system flexibility can be leveraged by scheduling electric DHW tanks at district level.

Quantitatively, Figure 3 presents the equipment costs against the effective electricity costs for the P2H technologies considered.

The effective electricity cost represents the cost to generate the effective thermal power, which for the case of the heat pump corresponds to the electricity tariff divided by the COP. This means that heat pumps with a high COP generate large amounts of thermal power for each electricity power unit, which brings down the effective electricity cost. For Joule effect technologies, the effective electricity cost is just the electricity tariff, assuming a 100% efficiency. The European electricity tariffs averaged over a year have be found in [28], applying the price for household consumers to the household level in the table, and the price for industrial consumers to the building and district level in the table.

It can be seen in Figure 3 that, as expected, in general heat pumps induce a higher equipment cost than electric boilers and DHW tanks, but over a long period of time they are cost efficient due to a
lower effective electricity cost. In this respect, heat pumps have the economic characteristics of a base load technology, as opposed to electric boilers and DHW tanks which are more suited for peak load and flexibility purposes. A similar conclusion is found [11], where the analysis of the viability of P2H on district heating shows that P2H via heat pumps is cost efficient at district level as a base load, in combination with biomass.

Looking only at P2H mixes, the combination of a heat pump and electric boiler with thermal storage is even more flexible when the heat pump can take a large share of the load [25]. In Figure 3, the Joule effect point that has zero effective electricity cost corresponds to the Qrad. Q.rad is promising cost efficient equipment, but the technology is not mature enough to assess its long term reliability.

Figure 3 can be further refined by sorting out the level, as done in Figure 4, which emphasizes on the clear equipment cost difference at household level between the technologies. In practise it means that heat pumps are not competitive at that level, and therefore more likely to be found at building and district level.

![Figure 4: P2H equipment costs at different levels (frequency distribution on the sample from Table 2).](image)

In addition, installation costs varie significantly depending on the type of HP, and should be considered alongside equipment costs, especially at household level or small scale developments. For instance, unlike air-to-air heat pumps, GSHP require drilling works to lay the collector, which increases the installed cost (Table 3).

![Table 3: Installed cost of household level heat pumps [29]](table)

The following table shows the total cost of ownership per kWh heat produced for different decentralized heating technologies, taken from [30].
The next table gives the total cost of heat for different district heating schemes without P2H technologies, using data on heat plants, distribution network and substation costs, also taken from [30].

Table 5: Cost of heat from different DH schemes (€/ kWh) for low energy buildings [30]

<table>
<thead>
<tr>
<th>Country</th>
<th>ASHP</th>
<th>GSHP</th>
<th>Gas boiler</th>
<th>Solar thermal</th>
<th>Electrical boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulgaria</td>
<td>€ 0.161</td>
<td>€ 0.199</td>
<td>€ 0.116</td>
<td>€ 0.121</td>
<td>€ 0.118</td>
</tr>
<tr>
<td>Denmark</td>
<td>€ 0.216</td>
<td>€ 0.249</td>
<td>€ 0.173</td>
<td>€ 0.129</td>
<td>€ 0.284</td>
</tr>
<tr>
<td>Finland</td>
<td>€ 0.173</td>
<td>€ 0.210</td>
<td>N/A</td>
<td>€ 0.122</td>
<td>€ 0.156</td>
</tr>
<tr>
<td>Ireland</td>
<td>€ 0.193</td>
<td>€ 0.228</td>
<td>€ 0.129</td>
<td>€ 0.125</td>
<td>€ 0.216</td>
</tr>
<tr>
<td>Italy</td>
<td>€ 0.194</td>
<td>€ 0.229</td>
<td>€ 0.156</td>
<td>€ 0.126</td>
<td>€ 0.218</td>
</tr>
<tr>
<td>Latvia</td>
<td>€ 0.174</td>
<td>€ 0.210</td>
<td>€ 0.115</td>
<td>€ 0.122</td>
<td>€ 0.156</td>
</tr>
<tr>
<td>Lithuania</td>
<td>€ 0.170</td>
<td>€ 0.207</td>
<td>€ 0.123</td>
<td>€ 0.122</td>
<td>€ 0.147</td>
</tr>
<tr>
<td>Portugal</td>
<td>€ 0.188</td>
<td>€ 0.223</td>
<td>€ 0.141</td>
<td>€ 0.125</td>
<td>€ 0.199</td>
</tr>
<tr>
<td>Slovakia</td>
<td>€ 0.184</td>
<td>€ 0.220</td>
<td>€ 0.120</td>
<td>€ 0.124</td>
<td>€ 0.188</td>
</tr>
<tr>
<td>Slovenia</td>
<td>€ 0.178</td>
<td>€ 0.214</td>
<td>€ 0.148</td>
<td>€ 0.123</td>
<td>€ 0.170</td>
</tr>
<tr>
<td>Sweden</td>
<td>€ 0.191</td>
<td>€ 0.226</td>
<td>€ 0.180</td>
<td>€ 0.125</td>
<td>€ 0.209</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>€ 0.187</td>
<td>€ 0.222</td>
<td>€ 0.128</td>
<td>€ 0.124</td>
<td>€ 0.196</td>
</tr>
</tbody>
</table>

All these technologies are generally available in all the power ranges given in Table 6.
3 CLUSTERING BASED ON CLIMATIC ZONES

This section focuses on the influence of the geographical zones on P2H technologies, considering climatic zones and building typologies. An important source of information for such topics can be found in some recent European projects: EcoHeatCool [31], Stratego [32] and PVsites [33].

3.1 CLIMATIC ZONES

In [33], a zoning map is defined to help determine the most appropriate technologies for near-zero energy buildings in different European regions. The map shown in Figure 5 combines climatic zones of similar characteristics (outside temperature, solar radiation) with the EHI and ECI.

![Figure 5: Climate chart for near zero energy buildings, combined with European Heating Index (red) and European Cooling Index (blue) [33]](image)

The building strategies will be specific to each of the 5 identified zones, in terms of insulation, glazing, heat recovery, ventilation.

With respect to P2H, it is assumed that only heat pumps are impacted by the climatic zones. The COP of heat pumps provided by the manufacturer corresponds to nominal conditions, with standard and constant boundary conditions, however in operational conditions, the COP will strongly depend on the in-situ heat source and heat load. Physically, the performance of a heat pump decreases with ambient temperature and increasing return temperature, with additional degradation when defrost is required. A Seasonal Performance Factor (SPF) is introduced in [34] to estimate the actual in-site performance of heat pumps. It can be seen from Figure 6 that the SPF of ASHPs varies between 2.4 and 3.4 in European modern residential buildings. A similar result for GSHP’s shows that their SPF varies between 3 and 4.6.
Looking at the type of heat pump distribution across Europe, the trend is that geothermal heat pumps (GSHP and WSHP) are preferred in cold climatic regions, whereas air source heat pump are preferred in warm climatic zones, as can be seen from Figure 7. In this context, an additional trend is that ASHP’s in Southern Europe are installed for cooling purposes, whereas GSHP’s and WSHP’s in Northern Europe are installed for heating purposes.

Figure 6: Seasonal Performance Factor of ASHP in Europe, residential buildings [34]

Figure 7: Number of heat pump units sold in 2015 normalised by the population. Left: geothermal; right: aerothermal. Maps drawn using data from [35]
3.2 AVAILABILITY OF GEOTHERMAL RESOURCES

Among the outputs of the Stratego project, a Pan-European thermal atlas was developed [36]. In Figure 8, a screenshot of the map shows that deep geothermal resources are widespread in Europe, with the exception of Scandinavia and the Spain-Portugal region.

\[ \text{Figure 8: Geothermal potential for district heating [36]. Suitable hot sedimentary aquifers and other reservoirs.} \]

In order to assess the local feasibility of heat pumps, the data layers need to show the shallow geothermal energy potential, permeability of the soil, presence of free ground around the building to install the heat collector.

Such detail maps are found at the level of cities, for instance for Amsterdam (Figure 9), but not at the continental scale.
3.3 ENERGETIC PERFORMANCE OF BUILDINGS

In [31], a European Heating Index (EHI) is proposed, to address the limitations of more traditional approaches such as the degree-day method. The degree-day method is a widely used method to estimate the amount of cold to counteract with space heating at a certain location. This is done by summing up all daily temperature differences between an effective indoor temperature and the daily average outdoor temperature for that location, if the outdoor temperature is lower than a specified limit temperature (threshold value). Since heat loss from a building is directly proportional to the indoor-to-outdoor temperature difference, it follows that the energy consumption of a heated building over a period of time should be related to the sum of these temperature differences over this period [38].

However, it does not account for the energetic performance of buildings, e.g. there are 10 times more degree-days in the north of Sweden than in the south of Italy, but the heat demand in the north of Sweden is not 10 times higher because of the insulation of the buildings. Therefore the EHI includes the heat resistance of buildings, so that the space heating demand is proportional to the index. Similarly, a European Cooling Index (ECI) is defined.
So according to Figure 10, the heat demand in Stockholm should only be 20% higher than the heat demand in Brussels. One limitation of this type of index is that it estimates a thickness insulation based on the degree-day method, which is purely a climatic classification. However, climate borders are different from political borders, and other factors will also contribute to the energetic performance of buildings.

This effect can be illustrated by displaying a building performance indicator over a European map. Figure 11 is drawn using data from the EU Building Stock Observatory [39], and represents the energy efficiency value of external walls of residential building in 2014. This value corresponds to a heat transfer coefficient (in W/m²·C) of the building envelope and is compiled from various sources for all EU countries.

Low values, such as in Sweden and Finland, indicate a high level of insulation, compared to higher values in Spain or Italy. It can be seen that some variations are not correlated to climatic zones, for instance Belgium has a much higher energy efficient value (1.5) than neighbouring France (1.2), Luxembourg (1), Netherlands (1.1) and Germany (0.9).
3.4 PRICE OF ENERGY

Besides climatic zones and national regulations, the energy prices play an important role in the energy mix of each countries and on the energetic performance of buildings and the means of heat production. For instance, the performance of buildings in Norway may not have been optimised in the past due to abundant hydro resources, and electric heating was popular in France due to the availability of nuclear power. It is beyond the scope of this report to analyse the complex links, but a few facts can shed some light.

In Figure 12 and Figure 13, the energy prices for industrial consumers over the period 2002-2007 are presented for Sweden and France. It is interesting to note that the electricity prices are consistently lower and less fluctuating in France than in Sweden (Figure 12) over this period. Over 80% of the electricity consumed in France comes from nuclear plants, whereas in Sweden this proportion is around 45% over the same period, the rest being hydropower for the main part.
Similarly, gas prices are lower in France than in Sweden over the same period. Some common fluctuations between the 2 curves can be attributed to market variability.

The choice of enforcing insulation regulations or choosing to develop district heating in a country can be driven by the local energy costs. These costs have been historically very different within Europe, as the previous figures show.

However, with the development of commodity markets for energy such as EPEX, the use of P2H technologies can be leveraged. This is particularly relevant in the context of excess electricity production, which can lead to negative prices on the power spot market. For instance, the EPEX intraday index fluctuates hourly, with occasional negative values (Figure 14). In such circumstances, it is beneficial to convert electricity to heat of gas via P2H or P2G and store for flexibility purposes.
2.5 POWER-TO-HEAT TECHNOLOGY INTEGRATION STRATEGIES

3.5 REPRESENTATIVE CONFIGURATIONS

3.5.1 ITALY

In 2010, less than 5% of the heat demand in Italy was supplied by district heating, and the Heat Roadmap recommends to increase this share to 60%. The roadmap also recommends to invest massively in building heat savings, which can be partly explained by the poor thermal performance of current buildings. It is interesting to note that the cooling demand in Italy is currently 10-15% of the heat demand, however the cooling demand is likely to increase, whereas the heat demand is likely to decrease as more heat saving measures are implemented in the buildings.

As far as P2H is concerned, Figure 15 shows that there is currently very little investment in individual and district heating (DH) heat pumps, and the roadmap recommends to increase the investment in such technologies – including electric boilers – while reducing the investments in fossil fuel production units and power plants.
3.5.2 EASTERN EUROPE

Eastern Europe has the particularity to have a relatively large share of DH in the final heat consumption for historical reasons (Figure 16).

However, the system infrastructure is ageing, and requires large rehabilitation investments. Also, regulations and energy cost are not favourable to DH, with gas prices lower for public than for DH companies, and with the end of government subventions subsequent to the soviet era.

The most common source of energy is fossil fuels, with VRE source slowly increasing their share (Figure 17)
Eastern Europe has a good potential for geothermal energy. The potential is currently best leveraged by Hungary and Poland using geothermal heat pumps.

3.5.3 SWEDEN

Sweden has pioneered the extensive use of GSHP nationwide in the 1970’s and 1980’s and is currently the third leading country in geothermal energy in the world [43]. In 2015, 20% of single family houses in Sweden are heated with a GSHP and the number of GSHP for large buildings is steadily growing. Sweden constitute an internationally unique example of P2H solutions in district heating systems, with 80% of the capacity installed during the 1980s, which means that the large heat pumps used have been in almost continuous operation for more than 30 years [9].

District heating stands for a large share of the total heating demand. Several different fuels are used for the Swedish district heating production, and a radical shift towards renewable energy has taken place since the 1970’s.
Since around 2013, biomass fuels have accounted for 60 per cent plus and waste heat for 8 per cent of the input energy in district heating production. The overall usage of heat pumps has decreased in the district heating system in recent years and the use of electric boilers has almost completely disappeared since the early 2000’s Figure 19. The heat from incinerating waste is used as the basis for district heating in several Swedish cities.

Figure 18: Energy use for heating and hot water in dwellings and non-residential premises in 2013, TWh [44]

Figure 19: Input energy used in the production of district heating, TWh [44]
3.5.4 GERMANY

By absolute numbers; Germany is, together with Poland, the biggest market for district heating in the European Union, with a big difference between West Germany, where the market share for DH is around 9%, and East Germany, where the market share is around 30% [45]. Despite an overall decline in district heat demand, the expected addition of new heating networks will the integration of more renewable energy capacity, in particular geothermal and solar heat [46].

In Figure 20, it can be seen that heat pumps are on the rise in Germany (especially since 2005), with an installed 10 million KW of heat pump capacity and a total usage of 9 billion KWh. ASHP and WSHP are the most common installations in Germany.

![Figure 20: development of heat pumps in Germany][47]

While deep geothermal energy does not have a significant share in the renewable market within Germany, near surface geothermal energy, suitable for GSHP, account for 6.7% of the German heat consumption (Figure 21).

![Figure 21: Renewables based heat consumption in Germany][47]
3.5.5 FRANCE

French district heating systems were initially developed the 1980s after the oil crisis, and their development recently accelerated with the introduction of VRE sources in DHN and associated subsidies. However, the DHN market share is only 6% of the national heat demand in 2015 [48]. This share is spread across the residential sector (55%), the service sector (39%), and the industrial sector (6%).

The main sources of energy used in French DHN are natural gas and solid waste (Figure 22).

Since 2009, a public fund subsidizes the development of DHN for collective housing, cities and private companies. In order to be granted the subsidies, DHN projects must fulfill some conditions on the share of VRE in the production mix, and on the density of the network.
4 REQUIREMENTS TO SUPPORT A DECISION ON THE USE OF P2H

It should be noted that defining a set of energy production and storage technologies that is optimal for a given district is a complex task, where all the different factors identified in section 3 are combined: environmental conditions, local resources, energy prices etc. In the context of PENTAGON, is it an integral part of WP4 and WP5 to propose some scenarios in which these factors are taken into account. Therefore, in the present section, some elements of decision are provided to choose a set of technologies for each typical eco-district configuration presented in D3.1, focusing on the requirements from the point of view of a district heating manager (section 4.1). A suggested set of technologies for each configuration of D3.1 is then proposed (section 4.2 and 4.3).

4.1 KEY PARAMETERS FOR HEAT PUMP PROFITABILITY

A successful district heating manager should always minimise both the heat generation costs and the heat distribution costs in any given market situation [49]. In this deliverable the focus is on P2H, however the competitiveness of P2H is often compared to conventional heat production plants such as gas or biomass plant. Therefore, some elements of comparison to such technologies are mentioned in this section. Furthermore, it has been seen from section 2.1 that heat pump systems are the most common form of P2H technology at district level, so in this section the profitability of heat pump systems compared to gas or biomass plant is briefly discussed.

From the operator point of view, the window of profitability for heat pump plants is narrow due to the large initial investment required, and large operating expenses cannot be withstood [50].

In Figure 23, some of the key requirements for a profitable heat pump system are presented.

![Figure 23: Key requirement for heat pump plant profitability over gas/biomass plants](image)
A brief explanation of the main criteria affecting the decision to use a heat pump plant over other types (gas, biomass) is given hereafter [11]:

- **The load factor.** For a set of energy prices (electricity, gas, biomass), a heat pump is profitable provided it operates for a certain amount of time per year, which represents the load factor. In the case of an analysis with the French market, a heat pump with a CAPEX of 1000 €/kWth consuming 100 €/MWh of electricity would require a load factor of 80% to be profitable in comparison to a biomass boiler. When a thermal storage is available, the load factor can be increased, by storing the excess heat production.

- **COP:** Combined to the energy price, the COP is the most critical criterion in the profitability of a heat pump. If the COP is too low (i.e. lower than 2.5), or the price of heat provided by gas/biomass is too low, then the heat pump is not profitable. Therefore, ensuring that the COP is high is important. The COP depends on the temperature of the heat source, but also on the supply temperature of the district heating. Therefore, operating a low temperature district heating network (50-50 C) allows to benefit from higher COP’s. A higher COP can also be achieved using a thermal storage, which will guarantee that the equipment operates at nominal power and will reduce the fluctuations in delivered thermal power. Finally, providing both cooling and heating is a way to maximize the COP.

- **CAPEX:** To be competitive with other technologies, heat pump plants must compensate a high CAPEX by delivering thermal power at a lower cost. Unlike energy prices, the CAPEX of heat pumps is a characteristic that can be relatively well estimated in the design phase of heat plant project.

- **Energy prices.** The comparison of the price of electricity, gas and biomass is obviously an important criterion. However, it can be difficult to include this factor when assessing the financial relevance of a heat pump plant over a biomass or gas boiler plant because of the uncertainty on the energy prices on the mid and long term.

### 4.2 RESIDENTIAL ECO-DISTRICT

The residential eco-district consists of residential single-user buildings, up to 250 houses (see D3.1 for details). Figure 24 shows the different network components of this configuration.

![Figure 24: Residential eco-district configuration](image)
In this type of eco-district, the choice is made to connect all the buildings to the district heating network. The energy is transferred from the district heating network to the building via a substation [49]. The heat can be stored in tanks, or used for space heating via water radiators. The heat can also be used for DHW (base line in Figure 24).

Therefore in this configuration, there is no P2H technology at household level. Thermal storage in the form of water tanks contribute to the flexibility.

At district level, a heat pump system can provide the base heating load, with a gas CHP or biomass boiler for the intermediate load and a gas boiler for peak load.

For the case where the eco-district lies in the vicinity of a river or the sea, the most cost efficient solution in the long term is to use a WSHP. As a reference, the example of Kingston Height presented in section 2.1.1 can be scaled by half to represent the current residential eco-district.

In the absence of a nearby body of water, or suitable grounding in the area, and with a mild climate, the preferred heat pump type is air-to-water, as in the Glasgow Housing Association example of section 2.1.3.

The P2H flexibility is improved by having an electric boiler, associated to a thermal storage at district level.

4.3 MIXED ECO-DISTRICT

The mixed eco-district consists of large buildings, having different purpose (residential, commercial etc...), with up to 20 large buildings (see D3.1 for details). Figure 25 shows the different network components of this configuration.

The mixed eco-district displays a wider variety of energy production and consumption components, so is more prone to flexibility strategies using P2H.

For the buildings connected to the district heating network, it is not relevant to consider having heat pump specifically for space heating. Instead, air-to-air heat pumps, providing space cooling and heating, are more relevant, especially for office buildings.

At district level, as with the mixed eco-district, a heat pump can provide the base heating load, with a gas CHP or biomass boiler for the intermediate load and a gas boiler for peak load. As previously,
the most favourable condition is to have a large body of water nearby, in which case the Kingston Height development is again a template configuration.

Depending on whether the heat pump at district level provides DHW or not, DHW tanks can be used at building or household level with a centralised scheduling of the tanks at district level. Here, it is assumed that it is more cost efficient to have small DHW tanks at household level rather than a large tank for the building, however a careful analysis should be undertaken, considering the DHW peak consumption, costs and charging/discharging time, which is beyond the scope of this report.

For the buildings that are not connected to the district heating network a medium size heat pump, with a thermal power of typically 50 kW is used for space heating and optionally DHW. The type of heat pump depends on the available energy resource, with in the order of preference:

- Access to a large body of water : water-to-water HP
- Access to shallow geothermal energy : ground-to-water HP
- Mild climate : air-to-water HP

The P2H flexibility is improved by having an electric boiler, associated to a thermal storage at district level.

### 4.4 SUMMARY

The different options discussed for each configuration of eco-district in section 4.2 and 4.3 are summarised in Table 7. The table does not elaborate on storage capabilities, as the focus of the present report is on P2H, however, the optimal combination of P2H technologies is closely tied to an adequate set of storage capability.

**Table 7: List of P2H technology for the considered configuration, with preferred choices highlighted in blue**

<table>
<thead>
<tr>
<th>Eco-district configuration</th>
<th>P2H Technology</th>
<th>Level</th>
<th>Application</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>Water to water HP</td>
<td>District</td>
<td>Space heating</td>
<td>Nearby body of water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DHW</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Air to water HP</td>
<td>District</td>
<td>Space heating</td>
<td>No nearby body of water</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DHW</td>
<td>Mild climate</td>
</tr>
<tr>
<td></td>
<td>Electric boiler</td>
<td>District</td>
<td>Space heating</td>
<td>Flexibility</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DHW</td>
<td></td>
</tr>
<tr>
<td>Mixed</td>
<td>Air to water HP</td>
<td>Building</td>
<td>Space Heating</td>
<td>Office buildings</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Space cooling</td>
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5 CONCLUSIONS

In this deliverable, a critical assessment of P2H technologies is carried out, with the objective to contribute to the detailed specifications of conversion technologies in T2.6. Commonly used P2H technologies are reviewed, with an overview of their typical characteristics and some relevant examples of use at district or building level. A comparison of the technologies considered shows that heat pumps are more cost efficient in the long term than electric resistance technologies, particularly for large scale developments. An analysis of European clustering shows that there are strong geographical variations in the use of P2H, which can be explained by the variety of climates and national policies. A focus on 5 countries or geographical zones (Italy, Eastern Europe, Sweden, Germany, France) illustrates this variability. Finally, a set of P2H technologies is recommended for the eco-districts of interest in the PENTAGON project, as described in D3.1.
6 REFERENCES


