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Context and content of the report

The European funded D2Grids project aims to define, demonstrate and commercialize a standard and replicable 5th Generation District Heating & Cooling (5GDHC) technology which can increase the share of RES produced heat & decrease GHG emissions in North-Western Europe (NWE). The project promotes modular "plug-&-play" components, as well as demand-driven supply of heat at all levels, from early designs to operations.

To achieve this, the D2Grids project will aim to reach 4 objectives:

- Ensuring the quality of products supplied by the industry
- Reduce the initial investment requirements (long-term objective: -20%)
- Train and educate all support functions (legal, finance, construction, etc.) to 5GDHC networks
- Build trust from potential investors and project developers

5thGDHC networks rely on 4 main features:

- Low exergy demand can be supplied by low exergy heat sources: low temperature heat sources at 15-40 °C supply the network (shallow and mid-depth geothermal heat, minewater, riverbed, sea, heat recovery)
- A profusion of demand supplied by a closed heat delivery loop, enabling a better supply and a higher balance between hot & cold needs
- The coupling of electricity and heat grids to create a complete energy system
- New business models and services such as flexibility, transparency, proof of local production, prosumers, etc…

Considering that standardisation is a key driver for cost reduction, ease of installation and low through-put time, the project team proceeded to a market survey of components available at the beginning of the project. This document studies the best available technologies or conception designs that enable fulfilling the features and their current market maturity.

It is organized in four chapters:

- The 1st chapter, "Thermal energy generation" aims at describing the low temperature energy sources that are used in 5GDHC.
- The 2rd chapter describes "Thermal Storage technologies" for which the use will increase with the development of 5GDHC.
- The 3rd chapter is dedicated to "Heat pumps" that are the core of 5GDHC networks.
- The 4th chapter shows that "Coupling of thermal and electricity network", which is an innovative challenge of 5GDHC, may bring additional features to the network.

1. Thermal energy generation

1.1. Low temperature energy sources

The evolution of the requirements for energy performance in the building sector (more efficient insulation, low temperature heating, etc.) lower the temperature requirements for the heat supply, which favours the emergence of low temperature district heating and cooling. Therefore, it becomes interesting to take advantage of renewable low temperature energy sources to fulfil the baseload of the heating & cooling demand.

Geothermal energy was already the main renewable low temperature source valorised for heating and cooling, and recently additional sources emerged such as minewater and sea.

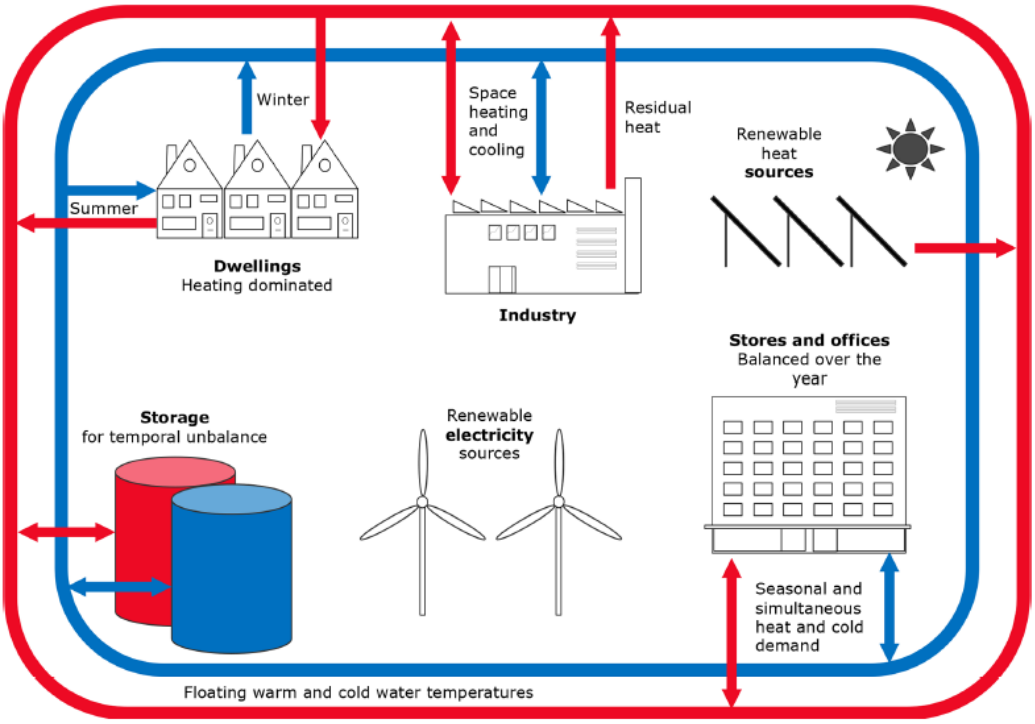

Figure 1 : Circular representation of a 5GDHC. [1]

1.1.1.Geothermal energy

1.1.1.1. Technical description

- Standard geothermal system

Geothermal energy is stored in the form of heat below the earth's surface. Today, geothermal energy is used for district heating, heating and cooling of buildings, electric power generation (deep geothermal), and many other direct or indirect uses.

Thermal energy can be collected from a few meters to several kilometres depth. The deeper the heat exchanger, the higher the temperature. A properly sized geothermal system can be operated for decades. Shallow geothermal energy – up to a few hundred of meters – can be used for heating or cooling buildings (depending on the climate conditions, heat pumps may be required). Energy from deeper layers can feed residential district heating networks without needing heat pumps, and can cover many other direct uses such as agricultural and industrial heat demand, or even generate electric power.

There are two different ways to gather geothermal energy (seeFigure 2):

- The first is to pump underground water through a well, exchange thermal energy, and then reinject the fluid back into the underground storage through a second well. Reinjection is necessary to maintain the amount of fluid in the aquifer and is often a regulatory obligation[1]. Such a system is called ***open loop***. The storage depth can reach several kilometres depending on the targeted level of temperature. The main open-loop systems are:
    - Naturally occurring aquifer storage
    - Water-flooded mines
- The second is to circulate a heat exchanging fluid (typically a mixture of water and antifreeze) into buried pipes, without any kind of water exchange with the underground. Such systems are called ***closed loop***. Popular closed loop systems are:
    - Horizontal (trenches) heat exchangers (1.2 to 2.0 m depth)
    - Vertical borehole heat exchangers (10 to 200 m or even more depth)
    - Energy piles (8 to 45 m depth)

Mine water systems are a subcategory of geothermal low-temperature heat sources, mainly used for district heating networks.

Over the operational period of the mines, encroaching ground water must be controlled so that the mining activity can be performed safely and efficiently. Once the excavation process is stopped, so is the dewatering process, which leads to the mines flooding. Hence, abandoned mines around the world represent a potential for geothermal energy, and especially for district heating and cooling.

Geothermal energy is harnessed through heat exchangers that can be set in various layouts:

- Horizontal loops (1.2 - 2.0 m depth)
- Borehole heat exchangers (10 - 250 m depth - vertical loops)
- Energy piles (8 - 45 m depth)
- Ground water wells (4 - 2500 m depth)
- Water from mines and tunnels (variable depth)
- Deep geothermal wells (2500 – 4000 m depth, for electricity generation)

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[1] In France, reinjection of the geothermal fluid into the same geological horizon is a regulatory obligation unless specific derogation is given (Article 17-2 of the 14th October 2016 Ministerial Decree)

Horizontal loops and energy piles are often used for single dwelling systems as they provide a rather small amount of energy that would not support the load of a large district network.

Ground water and borehole heat exchangers are suited to provide heat to single dwelling systems, butalso to large scale energy systems such as heating and cooling networks.

Flooded mines and aquifer systems are often used for larger systems and networks as they provide larger amounts of energy but also because they usually require higher initial costs to access the energy. An example of flooded mines heating is the Mijnwater network in Herleen, one of the pilot sites in the D2Grids project. The Paris Saclay network, also a pilot site in the D2Grids project, is a good example of aquifer heat generation.

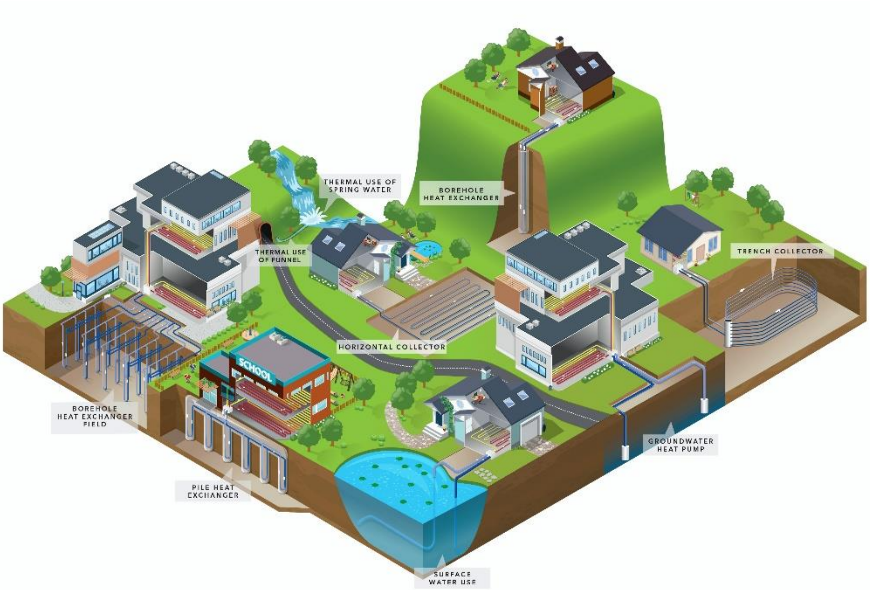

Figure 2 : Different types of near-surface geothermal heat exchanging systems.
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1.1.1.2. Market overview

The use of geothermal heat for district heating (DH) purposes is all but new. It dates to Roman ages: a DH system pioneered in year 1330 at Chaudes Aigues, in Central France and fed by the Par hot spring at 82°C is still operating to date.

Thanks to its geological past, Europe has many geothermal sources (Figure 3): medium and high temperature basins are present in most of the densely urbanized areas. These sources can feed DHC networks directly.

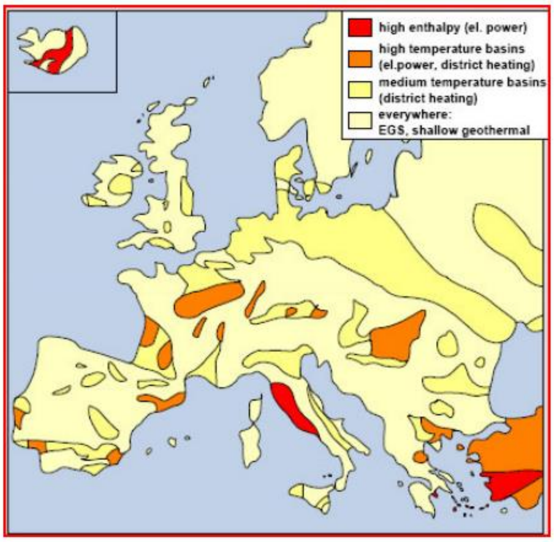


Figure 3: Geothermal resources in Europe [3]

Geothermal district heating accounted for over 9 GW_{th} of capacity in Europe in 2018 (1.7 GW_{th} in the European Union), with more than 300 districts in operation [20]. The number of new plants coming online each year is on an upward trend, with an average annual growth rate of 10% in recent years [1]. The development of geothermal energy as a source for heating and cooling is particularly dynamic in Germany, where 35 projects (deep geothermal) are planned or in developments, but many smaller or newer markets are also increasingly investing in geothermal energy, such as the Netherlands, Poland, and the UK.

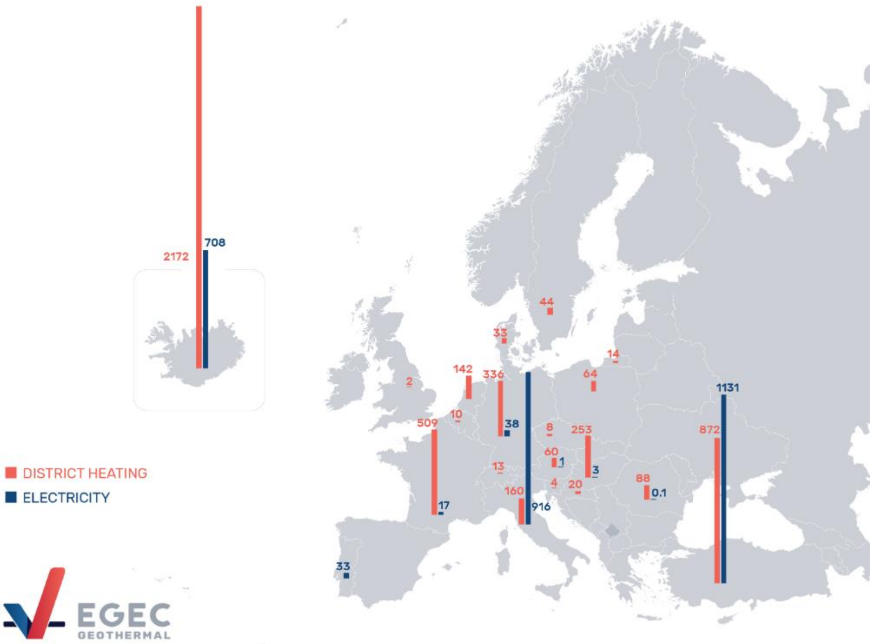


Figure 4: Installed capacity for electricity and district heating in 2017 (MW) [1]

1.1.1.3. Current Prices and evolution

Heating and cooling	Costs 2013 Average (€/MWh)	Costs reduction by 2030
Deep Geothermal - District Heating	42	5%
Geothermal Heat Pumps – large systems and Thermal Energy Storage (TES)	55	10%
Geothermal Heat Pumps – small systems	80	10%

Table 1: Geothermal heating and cooling prices

District heating systems may benefit from economies of scale if demand is geographically dense, as in cities, but otherwise the installation of the distribution piping will generate high capital costs.

1.1.2. Sea, riverbed and lake systems

1.1.2.1. Technical description

The use of ocean/sea/river/lake thermal energy is quite a new concept for thermal heating and cooling. These sources can provide water between 8°C and 20°C with a seasonal variation depending on the depth of the intake. These levels of temperature fit with the 5th Generation heating and cooling networks. Thanks to their low temperature, this kind of system can enable free cooling, reducing the electricity requirement, thus increasing the overall rate of renewables per kWh_{th}.

There are 5 systems in Europe using seawater as their main heat source, 3 of them are in Italy.

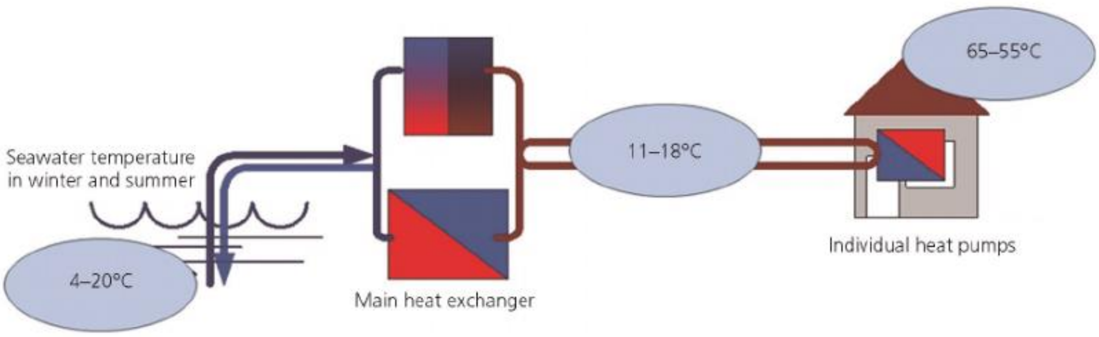


Figure 5: Schematic representation of a seawater heating system [21]

The seawater heating system extracts seawater and then processes it either via a heat exchanger or via a heat pump to supply an entire residential area with space heating and hot water.

In summer, when the temperature of seawater is higher than 11°C, only the heat exchanger is used. The heat exchanger feeds heated water to the local grid, drawing enough heat from the seawater to cover the needs of the clients. During winter, when the water temperature is lower than 4°C, the heat pump at the client's substation is activated.

The network provides around 800 homes for a total construction cost of 7.5 M€.

Another example is provided by the city of Värtan Ropsten, Sweden, the largest water source heat pump with a capacity of 180 MW. It was completed in 1988. The heat is fed at 80°C into the Stockholm district heating system and the return temperature is at 57°C.

The case of riverbed water has a bit more constraints: water contamination is usually higher due to moving waters, the flowrate of the river needs to be considered when designing the pump. The D2Grids pilot project in Glasgow targets to use heat from the riverbed as one of its main heat sources.

1.1.2.2. Market overview

While there is a great potential in NWE countries, this system is not developed. We may suppose that it is due to the lack of urban density in the vicinity of the resource. However, this resource can be developed in commercial harbour hubs, or touristic areas which often have huge thermal needs.

There are also a few examples of riverbed water as a heat/cold sources in Europe, such as the cooling network in Paris which is supplied mainly by the river Seine during winter.

1.1.3. Waste heat recovery

1.1.3.1. Technology overview

The ability to recover waste heat is directly dependent on whether the temperature of the heat recovered is in accordance with the temperature of the DHC.

For waste heat that has low temperature (< 100°C), it will be directly recovered through a heat exchanger or a heat pump (see chapter 3.1 for more details on heat pumps). For higher temperature waste heat, it cannot be recovered directly unless an additional process uses part of the heat and delivers low-temperature heat. One of these systems is the Organic Rankine Cycle technology as detailed below.

Organic Rankine Cycle

The Rankine Cycle is a thermodynamic cycle that converts heat into work. It is used to produce electricity from medium temperature heat (80 – 350°C). Organic Rankine Cycle technologies rely on vaporizing an organic working fluid that has a high molecular mass. This leads to lower maintenance on the turbine.

As detailed by Turbogen, the operation of an ORC is as follows (the numbers relate to those in Figure 6). "The ORC turbogenerator uses medium-to-high-temperature thermal oil to preheat and vaporize a suitable organic working fluid in the evaporator (4>5). The organic fluid vapor rotates the turbine (5>6), which is directly coupled to the electric generator, resulting in clean, reliable electric power. The exhaust vapor flows through the regenerator (6>7), where it heats the organic liquid (2>3) and is then condensed in the condenser and cooled by the cooling circuit (7>8>1). The organic working fluid is then pumped (1>2) into the regenerator and evaporator, thus completing the closed-cycle operation."

There is a necessity for cooling at the condenser level. Additionally, typical levels of temperature at the condenser are ~45°C input and 30°C output. Though this will vary depending on the system, it suits quite well with expected temperature levels in 5GDHC networks.

This opens possibilities for a double step waste heat recovery from exhaust fumes, industrial processes, or other processes that supply heat at suitable temperatures. The first step consists in producing renewable electricity, and the second in producing heat for local district heating.

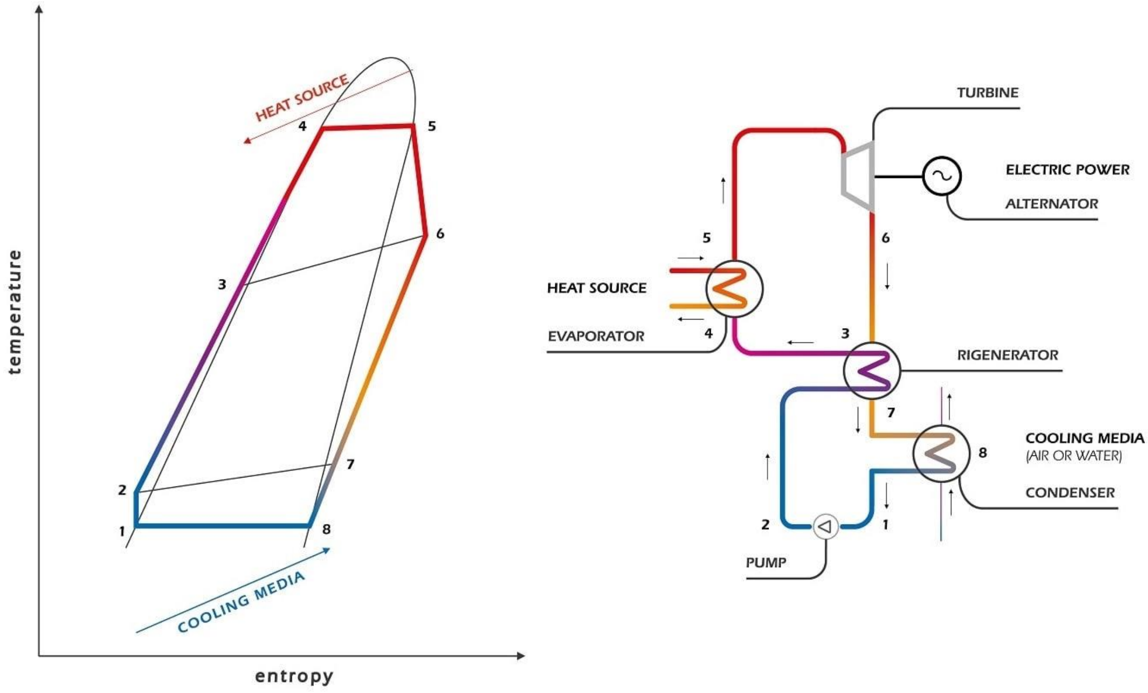


Figure 6 : Temperature to Entropy diagram of the working fluid in a typical ORC system (left), Schematic of a typical ORC system (right) [25]

1.1.3.2. Market overview

To understand the market potential of waste heat recovery, one needs to study the different potential sources: industrial processes, datacentres, etc.

Waste heat from industrial processes

Industrial waste heat represents a large source of heat in Europe but does not always deliver waste heat at temperatures directly suitable to that of 5GDHC networks.

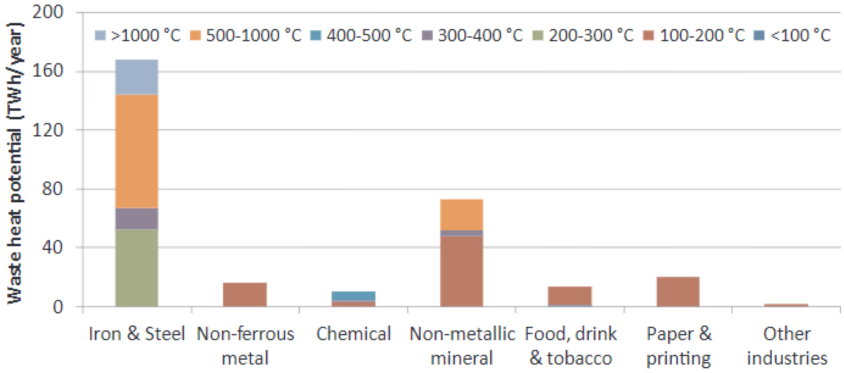


Figure 7 : Waste heat potential per temperature level across 6 main industries [11]

Heat at levels from 100°C to 300°C can be partly recovered for use in a DHC system through an ORC system. Higher temperatures may be recovered for other uses (including internal recovery).

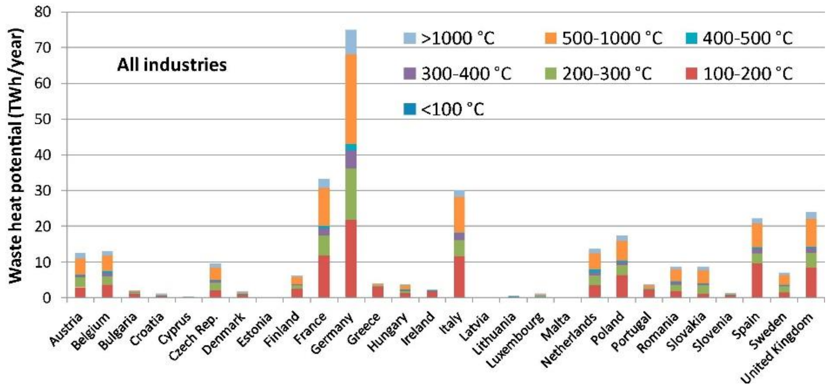


Figure 8 : Waste heat potential in each EU countries per temperature level in all industries. [11]

On the other hand, the food industry presents an interesting case as the temperatures are the closest to those required and direct recovery through heat exchangers or heat pumps may be implemented in some cases.

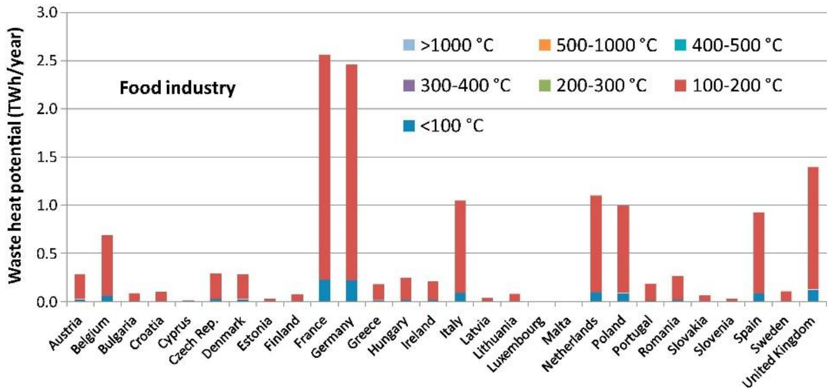


Figure 9 : Waste heat potential in each EU countries per temperature level in the food industry [11]

Waste heat from datacentres and the retail industry

Waste heat from data centres and the retail industry is available at low temperature: 30 to 40°C. This range of temperature is perfectly in line with the closed loop requirements of 5GDHC networks. Heat recovery will enable meeting the objectives of both datacentres that are seeking for energy efficiency and of the 5GDHC sector that hopes to rely on multiple decentralised low carbon sources.

Already a growing number of data centres are redirecting the heat from their hot aisles to nearby homes, offices, greenhouses and swimming pools. The ability to re-use excess heat from servers is being built into new data centres, helping to improve the energy efficiency profile of these facilities.

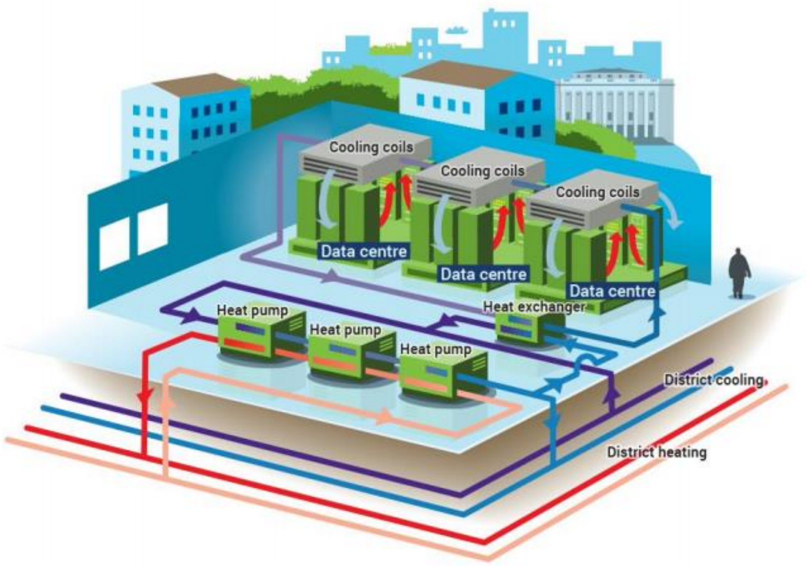


Figure 10: Heat recovery from datacentre integration in a District Heating and Cooling system [12]

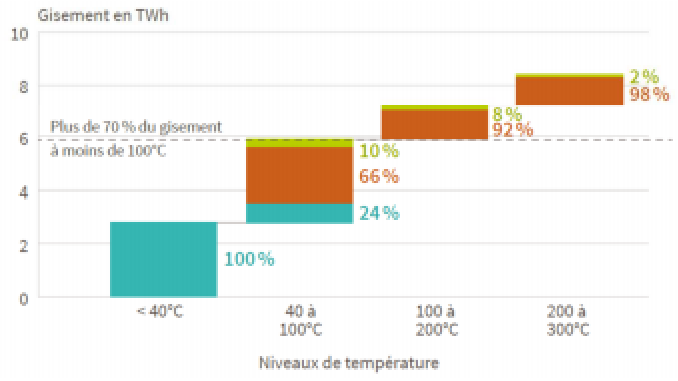


Figure 11 : Recovery heat potential in France from waste plants, datacenters and water purification, in TWh [27]
(**Turquoise** : datacenters, **Red** : waste plants, **Olive green** : water purification plants)

Waste heat from sewer systems

In residential or industrial areas, it is possible to recover heat from artificial water flows. At the building level, heat from waste Domestic Hot Water (DHW) represents a large amount of energy which can be captured back from the sewage system. In Oslo, about 8% of the thermal energy required by district heating is obtained by recovering heat from the sewage system. Several systems are already installed in France.

Downstream of industrial water treatment processes is also an ideal heat source as it is possible to find stable temperature water flows. In Berne, Switzerland, 60% of the heat demand is provided by extracting energy from treated water. In Aurich, Germany, a volume of 1200m^3/day of wastewater from a cheese and dairy manufacture supplies 80% of the peak heat demand.

To harness heat from the sewage water system, one must consider that the temperature of the wastewater stream should not go lower than 13°C as most treatment processes require a warm water stream. However, waste water effluents generally leave the buildings at temperatures above 27°C, leaving a 14°C window to harness the heat content.

Other waste heat sources

Any system generating excess heat may be eligible for waste heat recovery to supply 5thGDHC: metro airshafts, electrical HV-LV transformers, etc… The Bunhill network in London harvests both these energy sources.

Strategic Heat Synergy Regions

Depending on the available excess heat and the demand from buildings, several strategic heat synergy zones (SHSR) in Europe are identified where the excess heat covers a large part of the heat demand. The below figure gives a detail of 22 SHSR in Europe where waste heat is already partly recovered but could be expanded. The figure below it, details 18 SHSR where waste heat recovery could be of interest but is not yet well developed.

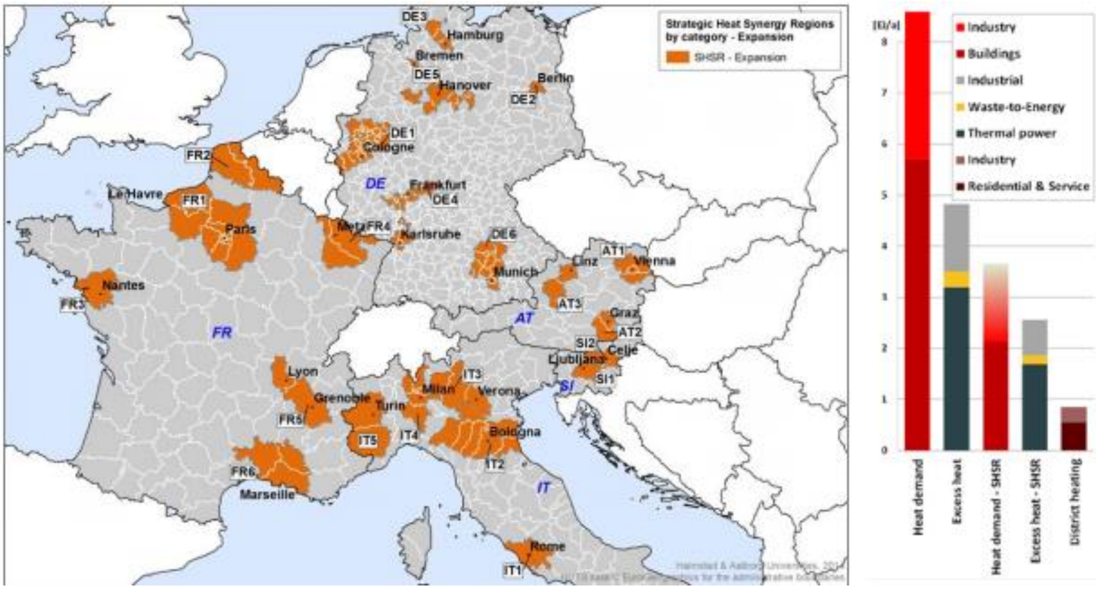


Figure 12 : 22 strategic heat synergy regions (SHSR) [10]

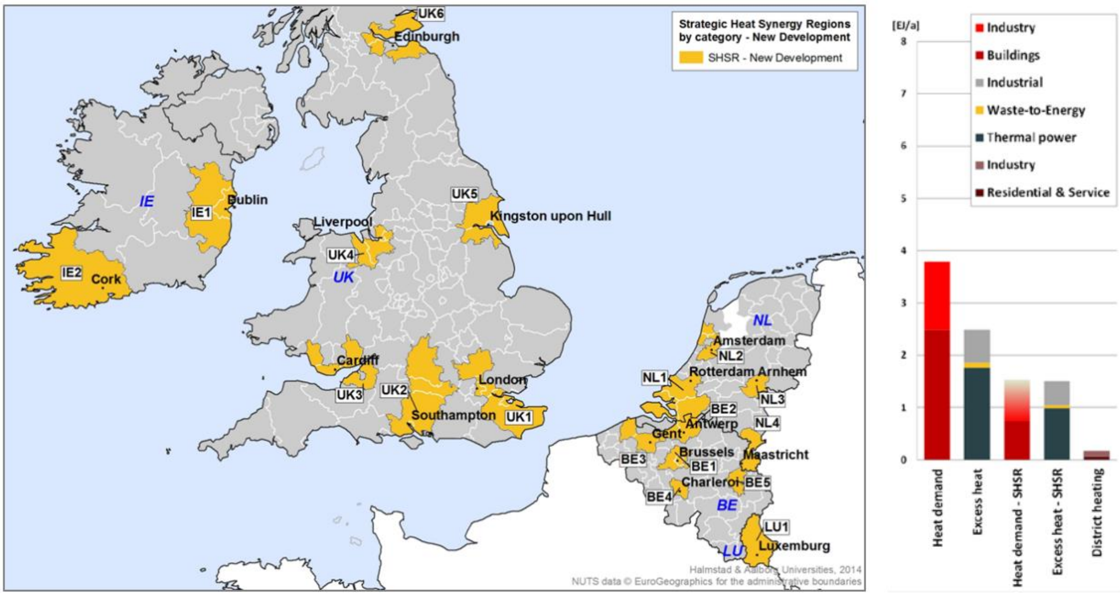


Figure 13 : 18 strategic heat synergy regions (SHSR) [10]

Depending on the recovery source, connection from the source to the DH may be complicated for administrative reasons. When collecting heat from an industrial player, an agreement needs to be reached between the firm and the DH operator to decide who should finance and own the recovery installation, as well as the retribution scheme.

In France in 2017, about 3% of the total heat delivered by DH networks was sourced from industrial heat recovery. The French government targets 39.5 TWh generated from renewable energy and recovery by 2030 (compared to 24.6 TWh in 2016).

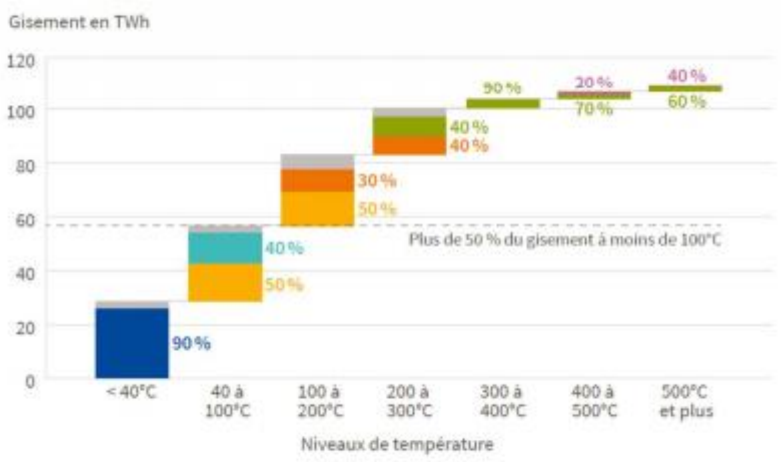


Figure 14 : Heat recovery potential in France in 2016 [27]
(**Dark Blue** : fluids from cooling systems (except compressors) ; **Olive green** : fumes from ovens ; **Yellow** : Drying machines ; **Red** : Fumes from heating systems ; **Turquoise** : cooling of air/water compressors ; **Purple** : sensible heat from the cooling of products out of ovens)

In most of the NWE countries the industrial heat recovery potential is far from being well exploited. To maximise the use of industrial heat recovery, the 14th article of the European Directive on Energy Efficiency expects any new major plant built to perform a cost-benefit analysis for heat recovery for district heating.

1.2. Solar thermal generation

The combination of multiple heat sources is beneficial, especially for large district heating schemes, as it allows shifting from source to source depending on specific conditions and market prices.

Therefore, in addition to sources especially efficient at low temperatures that aim at supplying the baseload and were described previously, DHC investors may decide to add other low carbon thermal generation capacity (at higher temperatures).

Of course, several of the technologies listed above may supply higher temperature heat (i.e deep geothermal or high T° waste industrial heat), but the cost of adapting this to 5GDHC networks functioning at low temperature may be too high. On the other hand, solar thermal generation supplies heat at relatively low temperature (80-100 °C) and is renewable. Therefore it may prove interesting for 5GDHC.

Solar thermal generation can provide heat to a 5GDHC network in two ways:

- Locally at the consumer scale, enabling them to reduce their consumption from the grid
- Directly contributing to the closed loop through hydraulic connection at the substation level, thus enabling the loop to lower its carbon emission ratio

Due to its specific production profile during the day, and its rather high temperature level (though quite low compared to other high temperature generation technologies), it is usually coupled to thermal storage.

1.2.1.1. Technical description

Most of the plants at the user level are composed of roof-integrated or roof-mounted solar collectors and pressurised collector systems with an anti-freeze mixture (glycol and water). They are designed to cover the summer heat load using diurnal water storages.

Recently, much like the regular PV panels for the electricity networks, district heating network developers started to install large scale ground mounted solar heat plants in order to increase the share of renewables in the heat supply.

The technology relies on the 'greenhouse effect'. Incident solar radiation passes through the transparent or translucent surface of the solar collector. The metal or plastic surface and glazed panels reduce the heat radiated back out, resulting in lower heat loss by the convection of heat from the hot absorbing surface. These types of systems are used for high temperature (up to 150°C).

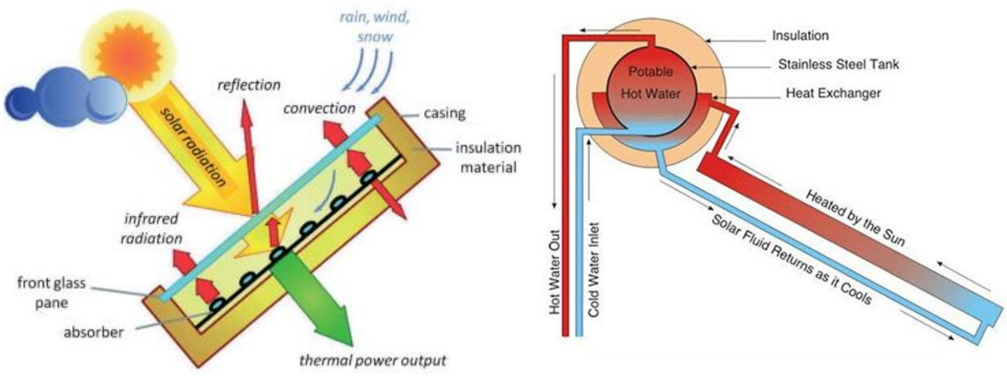


Figure 15 : Solar thermal: technical concept of flat pate collector (left) [13] and of a vacuum tube collector (right) [14]

Technology	Flat plate collector	Vacuum tube collector
Applications	➢ Highest market share ➢ Sanitary hot water ➢ Residential heating ➢ Absorption chiller	➢ Industrial heating ➢ District heating
Advantages	➢ Largely deployed ➢ Mature technology	➢ Better space efficiency ➢ Low efficiency reduction during operation
Disadvantages	➢ Efficiency decrease when the temperature increase ➢ Requires an auxiliary system (gas or electric heater…)	➢ Superheat sensitivity
Temperature range	➢ 50°C-80°C	➢ 100°C-150°C
B (optical efficiency %)	➢ 0,78	➢ 0,76
K (losses W/m²/°C)	➢ 2-4	➢ 1,2
Capex	➢ 700 €/m²	➢ 1200 €/m²
Opex	➢ 1% to 2% of initial investment	➢ 1% to 2% of initial investment
Suppliers	➢ Viessmann ➢ De Dietrich ➢ Heliopac	

Figure 16: Technical characteristics and prices of Solar thermal collectors (some data from [17])

1.2.1.2. Market overview

There are around 60 solar district heating and cooling systems in Europe, mostly in Denmark (31), Sweden (9) and Germany (8).

The technology is sufficiently mature to be deployed and will enable an increase in the share of renewable energy in district heating and cooling network.

Solar thermal installations can be roof-mounted or ground-mounted. Considering that DHC are mostly displayed in densely urbanized areas, ground mounted installation are less expected to be deployed in this context. However, for DHC in rural areas or small urban areas, ground-mounted solar thermal may have a key role to play. In the scope of the D2Grids project we expect to observe that multiple decentralized production means will be operated by the same actor as the one operating thermal production. Or we could also see several different stakeholders operating the production means and aa single operator for the system: this will require a third party or a smart-contracting system to exchange thermal renewable production (see also report "DT2.4.1. State of the art of blockchain and smart contracting").

1.2.1.3. Trends and innovation

➢ Limit fluid vaporization

Two technologies are increasingly known and used as a solution to the main constraint of thermal solar: vaporization of the thermal fluid when the temperature inside the captor increases. Those are :

- Drain back collectors: stops the fluid circulation at a temperature setpoint and evacuates it by gravitation to the storage tank.
- Thermally-protective coating (Viessmann) that limits the increase of temperature in the collector to a maximum of 150°C with the objective to reach a limit at 120°C.

➢ Hybrid production of thermal energy and electricity

Hybrid PV and thermal solar panels are PV panels with thermal collectors underneath the PV cells with a limited thickness. It has advantageous effects for both technologies:

  - The presence of the PV panels limits the superheating of the thermal collector to 75°C.
  - The thermal collector reduces the heating of the PV panels and improves their performance by 5 to 15%.

At the same time, hybrid systems answer a new market demand that dismisses the competition between PV and thermal solar.

➢ Solar thermal paired with heat pumps

The solar thermal system supplies the evaporator circuit of the heat pump with a stable and relatively high temperature (around 30°C), enabling the heat pump to produce high temperature for heating and sanitary hot water (60°C) with a good Coefficient Of Performance (COP) around 6. This good COP can only be achieved due to the limited temperature spread between the evaporator and the condenser. Compared to a standard thermal solar system, heat pump coupled systems are increasing in the market.

2. Thermal storage

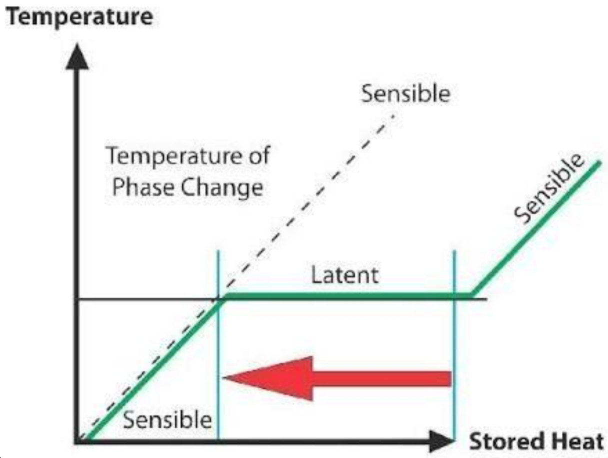
A key to implement DHC and to recover industrial waste heat is to be able to store thermal energy and deliver it later. Additionally, to ensure constant heat delivery even in case of peak heat demand, thermal storage is necessary. In DHC networks, both seasonal and daily thermal storage are used: daily storage enables dealing with daily peaks of demand at small scales (several delivery points) and seasonal storage enables storing excess heat during hot seasons and reduce the main generation requirements during winter (supplying the whole network).

Thermal energy storage (TES) groups technologies that store thermal energy by heating or cooling a storage medium to use it later[2]. For the majority, the storage medium can be similar for heating and cooling applications (i.e, the same material has a good capacity to retain heat or cool, and easily transfers heat). TES systems are generally used in collective heating and cooling networks as well as in industrial processes. TES technologies enable a better efficiency and reliability in the overall thermal system, as well as reductions in investments in heat production and running costs.

2.1. Technology overview

There are 2 main technologies which both rely on heat transfer fluid storing energy, either as sensible heat or latent heat (see Figure 17). The fluid receives heat or cold from a thermal production unit and delivers it to the thermal uses. Thermochemical storage is a 3rd technology group which uses the heat used or released by chemical reactions (see Figure 17). However, to date it is mainly applied to high temperature storage, thus it is not suitable for 5thGDHC applications. Therefore, we will not review it in this document.

[2] Though this report will focus on low-temperature heat storage, large amounts of information about high-temperature TES have been collected during the EU-funded Geothermica HeatStore project and may bring additional insight. See especially the deliverable "*Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned*" available online at https://ww.heatstore.eu/ (free of charge).



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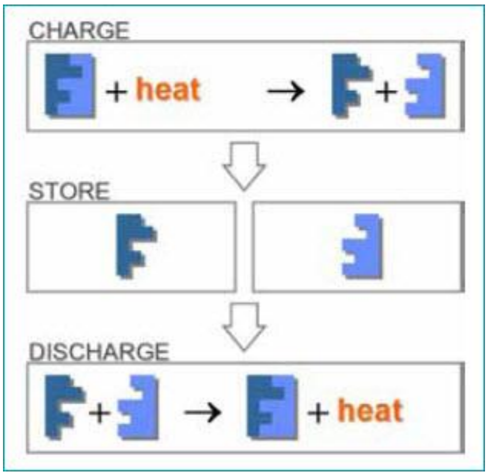


b)

Figure 17 : a) Illustration of sensible and latent heat, b) principle of thermochemical storage

The storage phase takes place when the external conditions are advantageous, and the discharge is used to shift the electrical or thermal consumption during peaks of use.

Aside from the price and geological compatibility, several parameters come in play when choosing a specific thermal storage application:

Feature	Description	Details / calculation
Storage capacity	Measures the maximum heat capacity that can be stored	
Efficiency	Measures the ratio of energy charged and energy delivered.	The equipment necessary to charge/discharge the heat storage medium is not 100% efficient, so the efficiency of the whole system is not 100%. $\frac{heat\ discharged\ (kWh)}{heat\ stored\ initially\ (kWh)}$
Heat losses	Measures the efficiency of the storage and the loss of heat over a given period	There may be heat leakage from the storage overtime, the lower the heat losses, the better heat is stored. $\frac{heat\ delivered\ after\ a\ given\ period\ of\ time\ (kWh) - heat\ charged\ initially (kWh)}{time\ passed\ (h)}$
Energy/power ratio	Measures the time during which the storage can supply the maximum power until depletion of the stored energy	$\frac{rated\ maximum\ heat\ energy\ (kWh)}{rated\ maximum\ power\ (kW)}$
Temperature range	Measures the maximum and minimum temperature at the entrance/exit of the storage	Some storage mediums or equipment cannot handle extreme temperatures
Power range	Measures the typical power ratings available for the technology	Depending on the size, the medium, the equipment, the price viability, etc... some technologies may not be available for certain power ranges.

Table 2: Definition of thermal storage performances

2.1.1.Sensible heat technologies

As seen on Figure 173, sensible heat is the heat stored or delivered by a storage medium when its temperature rises or decreases, while it remains in the same physical state (gas, liquid, solid). For this application, the most popular storage medium is water due to its low cost and availability. Hot water tanks are a mature technology used both for industrial and residential applications (i.e coupled with solar thermal heat, or hot water domestic tanks).

Water buffers (hot or cold) are a mature technology and are often installed in district heating and cooling networks as well as in industrial installations. The amount of heat stored depends on the temperature and the volume of the tank.

2.1.1.1. Tank TES

Tank TES consists of a concrete/steel tank (either under- or over-ground) thermally insulated and filled with water which uses the stratification phenomena to store cold water at the bottom of the tank and warm water at the top. Depending on the needs it can supply both hot or cold water.

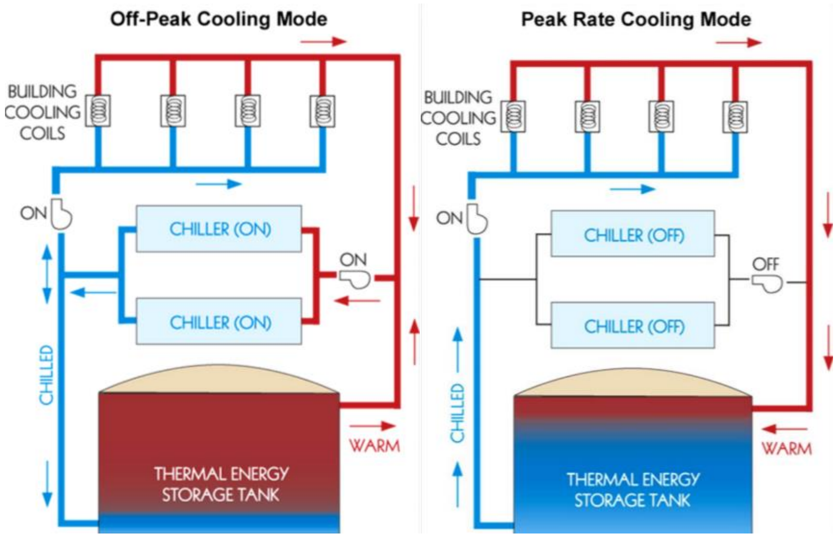


Figure 18 : Operating principle of a tank thermal energy storage used for storing cold water. [32]

2.1.1.2. Pit TES

Pit storage is very similar to the Tank TES, except the storage volume is dug underground and covered with a heat insulated roof. The inner walls are covered with a polymer lining to retain water but could also be made of concrete. PTES are largely used in Denmark, where 5 installations can store up to 200 000 m^3 of water, at temperatures going up to 90°C. One of the drawbacks of PTES is that they have a large ground-surface footprint because the surface on top of the pit is rendered unconstructible. This makes them unsuitable for urban areas. Gravel-water mixtures as storage medium in PTES installations may reduce this drawback.

Figure 19 : Picture of Dronninglund Pit Storage under construction [33]

2.1.1.3. Borehole TES

This technology makes use of the underground heat capacity. Water flowing in a large number (several hundreds) of sealed heat exchangers (buried U-pipes) collects/delivers heat from/to the underground. The heat exchange happens solely via conduction, there is no underground water pumping.

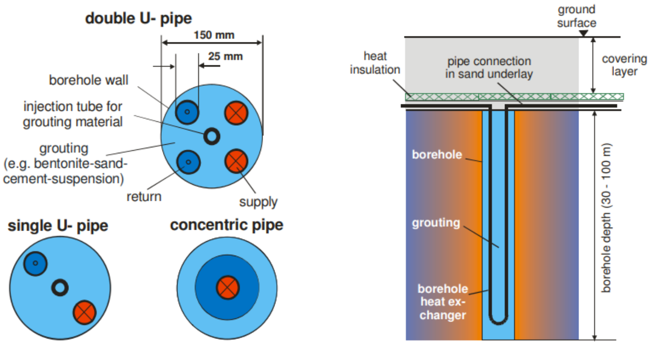


Figure 20: Common types and vertical section of boreholes heat exchangers [39]

The thermal losses of the storage depend on the thermal and hydraulic properties of the subsurface, the shape of the storage volume, the regional groundwater flow and the heat losses to the surface. Therefore, BTES can only be implemented in geological formations that have a high thermal capacity and low heat permeability, such as rock or water saturated soils with no or very little groundwater flow.

Because of the low heat conductivity of soils, BTES often have to be coupled to Tank TES in order to satisfy the quick response needs of a DHC network.

2.1.1.4. Aquifer TES

Aquifer storages use the self-contained naturally occurring underground water layers (aquifers). During discharge, hot water is pumped from the aquifer to provide heating power where required and returned at a lower temperature to the aquifer. During recharge, the flow is reversed: cooler water is heated and returned to the aquifer.

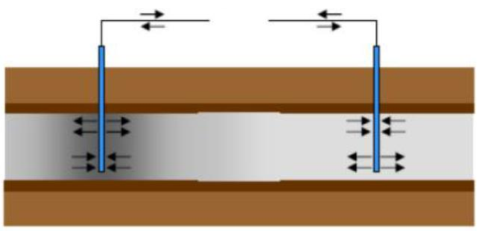


Figure 21 : Concept of an aquifer TES [31]

Most ATES operate around or below 30°C, making it a suitable technology for 5GDHC. The advantages of ATES systems include very large storage potential, low operational costs and high long-term profitability. Challenges include high return temperature requirements and hydrogeochemical challenges (precipitation or scaling in wells, pipes and heat exchangers.

To date, only 5 high temperature ATES, operating at temperatures above 60°C are in operation worldwide.

2.1.1.5. Main characteristics

Type	Tank	Pit	Borehole	Aquifer
Applications	▪ Heating and cooling network ▪ Industrial installations (heat recovery, CSP) ▪ Residential installation (hot water)	▪ Heating and cooling network ▪ Industrial installations (heat recovery, CSP)	▪ Heating and cooling network ▪ Industrial installations (heat recovery, CSP)	▪ Heating and cooling network ▪ Stand-alone large buildings
Advantages	▪ Cheap and mature technology ▪ Operates both in a continuous mode or on charge / hold /discharge cycle	▪ Technology under development ▪ Operates both in a continuous mode or on charge / hold /discharge cycle	▪ Operates both in a continuous mode or on charge / hold /discharge cycle ▪ Easy expansion by adding boreholes ▪ Reliable simulation tools	▪ Technology under development ▪ Operates both in a continuous mode or on charge / hold /discharge cycle
Disadvantages	▪ Low energy density ▪ Low power / energy ratio	▪ Ground-surface footprint ▪ Sensitive to quality of execution	▪ High investment cost ▪ Limited available power and low discharge T°C	▪ Discharge Temperature ▪ Environmental constraints (hydrothermal footprint) ▪
Cost	▪ about 1 €/kWh	▪ 0,3 – 1 €/kWh	▪ 0,4 – 4 €/kWh	▪ 700 – 1300 €/kW[3]

Table 3: Thermal storage main characteristics

2.1.1.6. Typical performances

Type	Tank	Pit	Borehole	Aquifer

[3] for ATES we do not refer to energy capacity in terms of kWh, as for aquifers size is usually expressed in maximum rate at which heat can be extracted from well at a single time.

Energy intensity[4]	▪ 5 – 80 kWh/m³ depending on the temperature spread and the size	▪ 30 – 50 kWh/m³	▪ 15 – 30 kWh/m³	▪ 30 – 40kWh/m³
Temperature range	▪ 5°C / 95°C	▪ 5 / 95 °C	▪ 5 / 90°C[5]	▪ 2 / 20°C (shallow) ▪ 2 / 8°C (deep)[6]
Energy /power ratio	▪ 4 - 12 hours	▪	▪	▪
Life time	▪ >20 years	▪ >20 years	▪ >30 years	▪ >30 years
Storage time	▪ Day – year (industrial) ▪ Day - week (domestic)	▪ Day-year	▪ Year (50% heat loss/year)	▪ Year
Power range	▪ 10 kW – 2 MW	▪	▪	▪

Table 4: Thermal storage performances

2.1.1.7. Ease of installation

Type	Tank	Pit	Borehole	Aquifer
Preparations / conditions required	▪ Excavation of tank volume for underground tanks ▪ Stable ground conditions ▪ preferably no groundwater	▪ Excavation of pit volume ▪ Stable ground conditions ▪ Preferably no groundwater	▪ Drillable ground ▪ High heat capacity ▪ Moderate thermal conductivity ▪ Low hydraulic conductivity ▪ Low natural groundwater flow	▪ natural aquifer layer with high hydraulic ▪ Confining layer on top ▪ No or low natural groundwater flow ▪ Suitable water chemistry at high temperatures

[4] The energy intensity can vary based on DeltaT and Cp of the medium, these are indicative ranges for comparative purposes
[5] These are technically feasible temperature ranges. Regulations may limit maximum temperature.
[6] These are technically feasible temperature ranges. Regulations may also limit maximum temperature (e.g. in France there is a limitation to 32°C return-temperature of the water to the aquifer).

Size of module	▪ 5 – 15 m deep ▪ Above ground volume	▪ 5 – 15 m deep	▪ 30 – 100 m deep[7]	▪ 5 -100 m aquifer thickness
Maintenance	▪ General cleaning	▪ Yearly water quality check and diving for verification of liners ▪ Detection of leakages	▪ Verification of fluid quality	▪ Maintenance of the underground pump

Table 5: Thermal storage operational data

2.1.1.8. Innovation

➢ Super insulation and floating ceiling

In order to reduce heat losses in tank TES, research is looking into new insulation techniques and materials. Additionally, floating ceilings would suppress the need for pressure regulating air and would enable to always pump water at the highest temperature, reducing overall heat losses.

➢ Molten salts

Though water has the highest heat storage potential, at ambient pressure it can only operate below 100°C. Molten salts allow to operate at ambient pressure while reaching much higher temperatures (>500°C) and can be used both as heat receiver at the source level and as thermal storage, improving the overall efficiency.

➢ Stratification enhancers

In both pit and tank storage, stratification plays an important role in reducing heat losses. Both chemical and mechanical systems can enhance this phenomenon.

➢ High-temperature UTES

Underground TES generally happens at low temperature (below 40°C). Working at high-temperature (40/90°C) would enable recovering high-temperature heat from industrial processes or power plants. Research would need to ensure that high-temperature has no impact on the geological ecosystem in BTES and ATES.

2.1.2. Latent heat

Latent heat technologies rely on the heat stored and released by materials when they change physical state (gas, liquid, solid). The heat is mainly stored in the phase-change process and it is directly

[7] Though the regulatory framework often has deeper limitations (e.g 200m in France), 100m is understood to be a limit to maintain optimal shape and reduce thermal losses.

connected to the latent heat of the substance. Generally, it is more common to find solid-liquid latent heat technologies because liquid-gas technologies would require handling the high volume- or pressure-difference between the liquid state and the gaseous state.

Alike sensible heat storage, the simplest medium is water/ice. On the other hand, the heat density increases and thus the storage volume is reduced.

2.1.2.1. Ice tank

An ice tank relies on the water/ice phase-change: it contains water that is changed in ice during the charge cycle and releases energy when melting the ice during the discharge cycle. Depending on the temperature requirements, two systems exist:

- Internal melting: The heat exchanger is used both for cooling the water from liquid to ice during the charge phase and for cooling the fluid during the discharge.
- External melting: The water/ice is the refrigerant of the circuit. The heat exchanger is only used for cooling the water from liquid to ice. This technology is mostly used in the dairy industry.

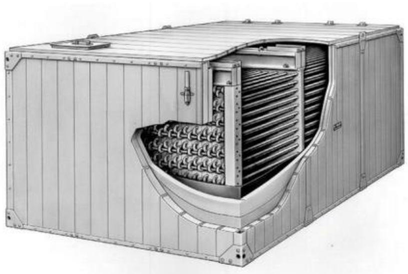


Figure 22: Baltimore Aircoil Company ice tank [34]

2.1.2.2. Ice slurry

The term "ice slurry" refers to a homogenous mixture of small ice particles and liquid. The amount of ice can be as high as 60% in the storage but needs to be lowered to 25% for the distribution. An ice slurry is produced by a specific ice generator.

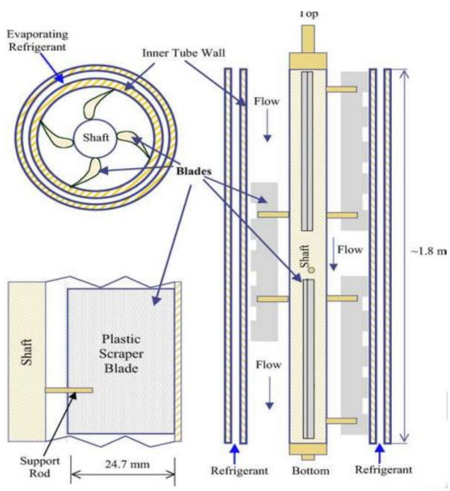


Figure 23 : Concept of an ice slurry generator [35]

The liquid can either be pure freshwater or a binary solution with additives such as glycol. Ice slurry storages have a high energy storage density because of the latent heat of fusion of the ice crystals. It also has a fast cooling rate due to the large heat transfer surface area created by the numerous particles. The slurry maintains a constant low temperature level during the cooling process and provides a higher heat transfer coefficient than water or other single-phase liquids.

Ice slurry generators are differentiated by the type of ice particles they generate. This technology is not very commercialized in Europe yet, and Japan is known to have the largest number of installed ice slurry systems.

Figure 24: Ice slurry generator system [36]

2.1.2.3. Phase change materials (PCM)

Phase Change Materials (PCMs are materials, either synthetic or natural, which have a high latent heat. Depending on the fusion temperature and the required applications, various materials can be used as a medium for latent heat/cold storage. The use of PCMs in energy storage is quite recent. The great diversity of PCMs makes them suitable both for hot or cold storage but nowadays they are mostly developed for hot storage. The most widespread materials are paraffins (organics), hydrated salts (inorganic) and fatty acids (organics).

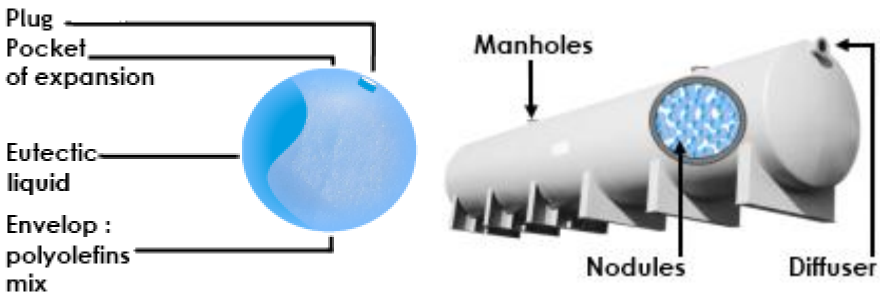


Figure 25: Cristopia PCM system, storage tank (left) and nodule structure (right) [37]

2.1.2.4. Main characteristics

Type	Ice tank	Ice slurry	PCM
Applications	▪ Industrial network ▪ Cooling network	▪ Food industry (i.e. breweries, central kitchen, etc.) ▪ Cooling network	▪ Nowadays only developed in concentrated solar power plant
Advantages	▪ Mature technology ▪ High energy density	▪ High energy density in the distribution network that enables to reduce the size of piping ▪ Reduce the size of exchangers due to the phase change energy density	▪ High energy density -> reduce the volume of storage ▪ Wide range of temperature
Disadvantages	▪ Charge cycle is long and adapted to a night charge ▪ Need a cold production below 0°C which is not common in a 5GDHC	▪ Investment price ▪ Not mature technology no wide commercial uses ▪ Need a cold production below 0°C which is not common in a 5GDHC	▪ Not mature on a commercial scale, few projects exist ▪ Risk of toxic material leakage ▪ Low thermal conductivity ▪ Phase change temperature range may be wide (°C to 10°C to achieve a complete phase change) ▪ Poor long-term stability
Cost	▪ 50€/kWh	▪	▪ > 100 €/kWh

Table 6: Thermal storage characteristics

2.1.2.5. Performances

Type	Ice Tank	Ice slurry	Phase Change Materials
Energy intensity	▪ 90 kWh/m3	▪ 25-50 kWh/m3	▪ 40 – 200 kWh/m3
Temperature range	▪ 2 / 20°C	▪ 2 - 5°C	▪ Large range of temperature from -30 °C up to 1200 °C
Charge Cycle	▪ 6 - 12 hours	▪ 6 - 12 hours	▪ 3 000 – 5 000 hours
Life time	▪ >20 years	▪ >20 years	▪ 15 years
Storage time	▪	▪	▪
Power range	▪ 100 kW – 5 MW	▪ 50 kW – 1-2 MW	▪ > MW

Table 7: Thermal storage performances

2.1.2.6. Main manufacturers

Type	Ice Tank	Ice slurry	Phase Change Materials
Manufacturers names	▪ Fafco ▪ Baltimore	▪ Axima (pilot installation)	▪ PCM product ▪ Cristopia

Table 8: Thermal storage manufacturers

2.1.2.7. Innovation

➢ Diversification of ice slurry applications

Ice slurries are currently mainly used in the food and dairy industry. Due to its high cooling potential coupled to its low GHG emissions, it is now being researched to suit diverse applications. That includes district cooling as well as medical cooling.

➢ Passive PCMs in buildings

PCMs present a high energy density as well as a constant temperature heat exchange, therefore they have a high potential in being used as integrated heat storage in buildings. Both increasing the storage capacity of the buildings and reducing the cycling of heat pumps.

➢ PCM slurries

PCM slurries would benefit from both enhanced energy transfer from convective heat transfer and increased heat storage from PCMs.

➢ Higher energy density

Higher energy density technologies may prove useful to ensure proper deployment in areas where physical constraints limit ground footprint.

2.2. Market overview

The most popular and commercial heat storage medium is water, which is largely deployed in residential and industrial applications as well as district heating. Underground storage of sensible heat in both liquid and solid media is also used for large-scale applications. This technology is mature, easy to size and has no technical constraints.

Phase Change Materials (PCMs) for storage are already used in Concentrated Solar Power plants and are bound to increase for both heating and cooling needs. To date, PCMs for cooling needs have not been demonstrated.

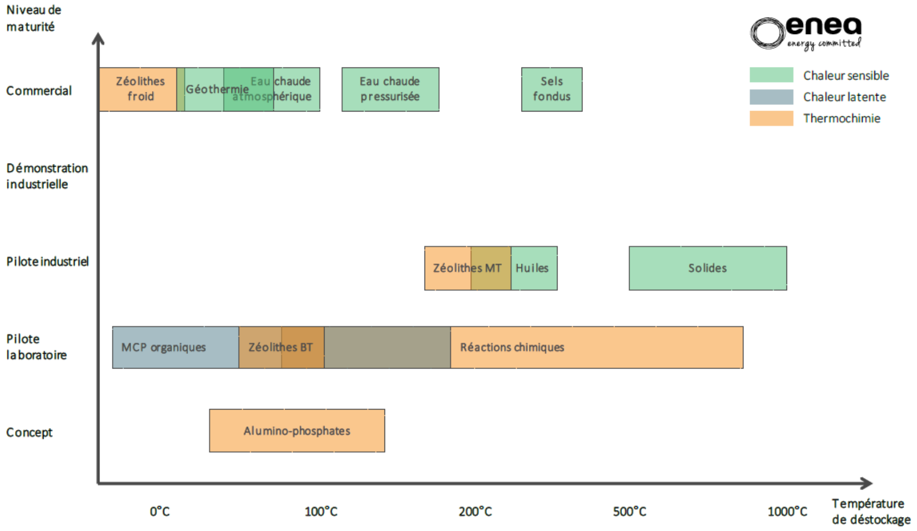


Figure 26 : Maturity level and discharge temperature for thermal storage mediums [38]

2.2.1.France

The French PPE (Multiannual Energy Plan) intends to foster investment towards geothermal heat storage technologies through the national Heat Fund.

In France, DHC networks that supply over 50% of renewables and waste heat get a VAT discount. Additionally, it is considered that 16 TWh of waste industrial heat are located close to existing DHC networks. Should these networks invest in TES to store the excess industrial heat, they would benefit from this VAT discount. Germany

The first designs of seasonal thermal storage entered in operation between 1996 and 2000 in Germany. They were either tank, pit, aquifer or borehole storages, with both water and gravel/water mixture as heat storage medium. The second and third generation were installed from 2000 to 2008 as part of solar-assisted district heating networks.

In 2017, Germany had 30 TWh of heat storage installed, covering the needs of 6.8 million citizens.

2.2.2.Netherlands

Seasonal thermal energy storage has been used in the Netherlands for 25 years, and mainly aquifer storage. The country is considered one of the frontrunners on this technology.

However, only 220 thousand non-residential buildings have adopted this technology. This is largely due to the low prices of gas in the country.

2.2.3. United Kingdom

For district heating applications, tank thermal energy storage is the main technology used in the UK and is used for intra-day storage.

There are a few projects for seasonal storage (borehole and aquifer mainly) but they are used for non-domestic uses and not included in district heating networks.

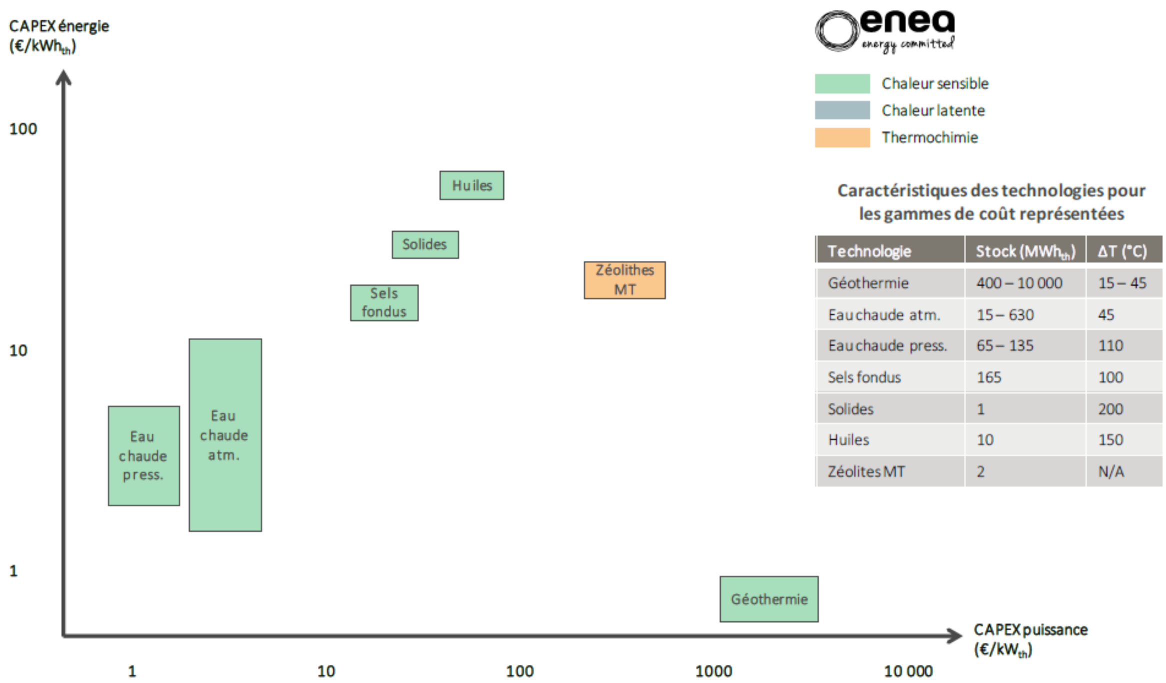
2.2.4. Belgium

As in other countries, several systems (borehole and aquifer) have been in operation since the late 90s for residential applications.

2.3. Prices and evolution

Typical prices for heat storage installations are currently in the range of 50 – 250 €/kW. Prices for PCM latent heat are expected to decrease in the coming years should these materials be applied in buildings to improve energy efficiency.

Prices for large water heat storages may not decrease as much as there are extensive civil works costs necessary to build the storage installations.



Technologie	Stock (MWh$_{th}$)	ΔT (°C)
Géothermie	400 – 10 000	15 – 45
Eau chaude atm.	15 – 630	45
Eau chaude press.	65 – 135	110
Sels fondus	165	100
Solides	1	200
Huiles	10	150
Zéolites MT	2	N/A

Figure 27 : Price positioning per energy and power of several thermal storage technologies [38]

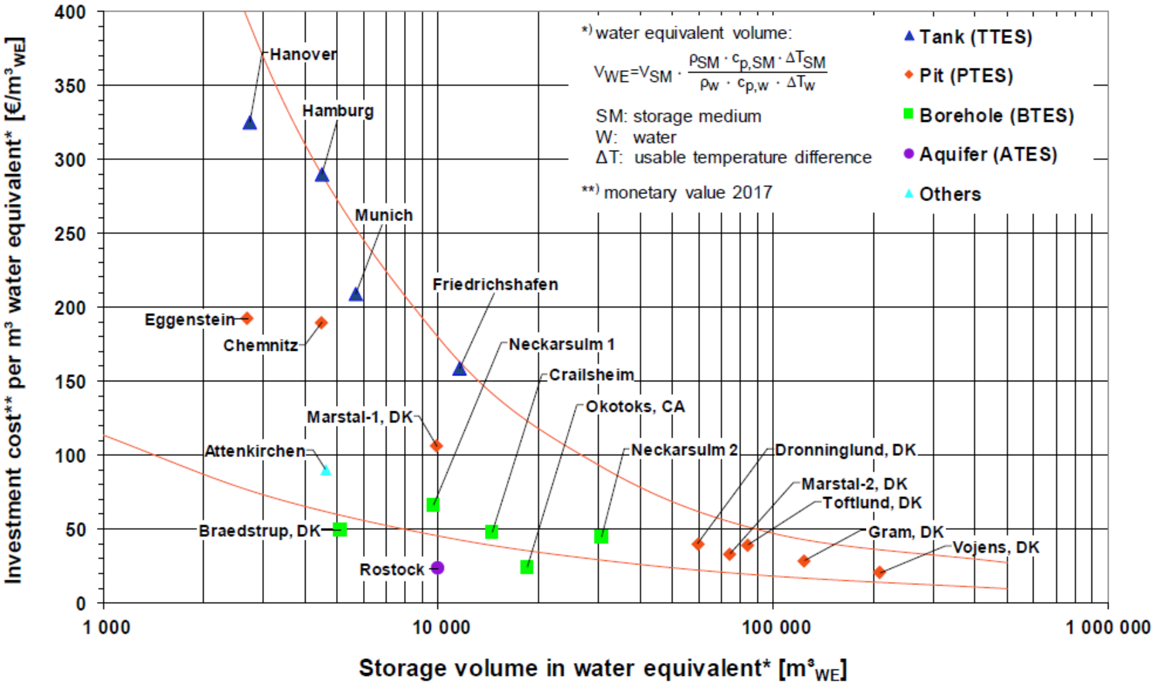


Figure 28 : Specific investment cost for large-scale high-temperature thermal energy storages (without design, connecting pipes and equipment in the production plant, without VAT) [41]

3. Heat pumps

Heat pumps are at the heart of the 5GDHC networks. As a matter of fact, temperature requirements for domestic and tertiary uses are 50°C to 55°C for DHW (Domestic Hot Water) and 30°C to 60°C for heating whereas 5GDHC operate around 15°C to 30°C (so-called low-temperature). Therefore, heat pumps are required to extract heat from the network, to heat up the domestic water and/or to provide cooling

In low-temperature district heating & cooling networks (LTDHC), the water delivered by the network and the load requirements from the domestic water system present favourable conditions for operating heat pumps and enable the highest Coefficients of Performance (COP).

3.1. Technology overview

Mechanical heat pumps exploit the physical properties of a refrigerant. The heat pump compresses the refrigerant to make it hotter on the area requiring heat and releases the pressure at the side where heat is absorbed.

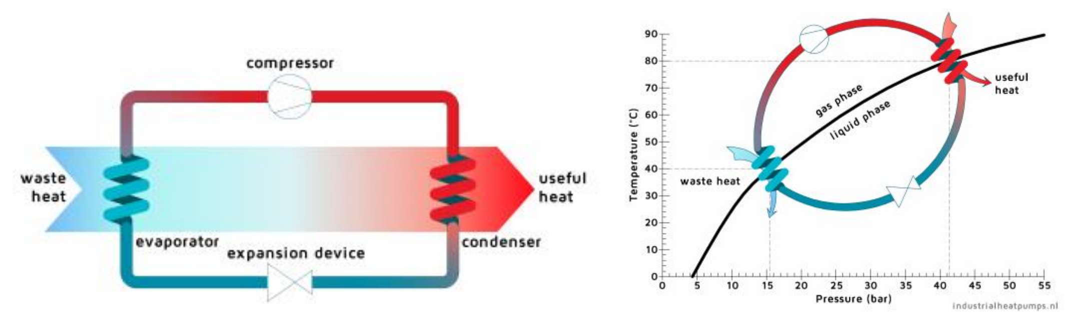


Figure 29 : Principle of a heat pump [42]

As shown in Figure 17, the working fluid, in its gaseous state, is pressurized and circulated through the system by a compressor. On the discharge side of the compressor, the now hot and highly pressurized vapor is cooled in a heat exchanger, called the condenser, until it condenses into a high pressure, moderate temperature liquid. The condensed refrigerant then passes through a pressure-lowering device also called a metering or expansion device. This may be an expansion valve, capillary tube, or possibly a work-extracting device such as a turbine. The low-pressure liquid refrigerant then enters another heat exchanger, the evaporator, in which the fluid absorbs heat and boils. The refrigerant then returns to the compressor and the cycle is repeated.

This process enables efficient heat generation with an average ratio of 1 kWh of electricity consumed for 4 kWh of heat delivered (COP = 4) and 3 kWh of cold (EER = 3). From this cycle, there are different kinds of uses depending on the external heat/cool sinks which can be: air, water, oil, etc.

A variety of refrigerants are available, which have different operating conditions and impact on the efficiency of heat pumps.

This single thermodynamic system enables 3 types of exploitation:

- Cold OR Hot production

The thermodynamic cycle is exploited only to produce heat (heat pump), or only to produce cold (chiller).

- Reversible system

The product will generate both heat and cold from the thermodynamic system, but not at the same time: through a valve derivation system, condenser and evaporator switch their roles regarding the need.

- Thermo-frigo-pump

A hydraulic design enables the user to consume both the heat and the cold produced by the same machine, at the same time. This design is typically exploited in 5GDHC because the main production (hot in winter, cold in summer) enables "recovering" the secondary need (cold in winter, hot in summer).

When choosing a heat pump, it is important to check the following performance parameters:

Feature	Description	Details / calculation
Heating power	Measures the maximum heat that can be delivered	-
Cooling power	Measures the maximum cold that can be delivered	-
COP (Coefficient of Performance)	Measure of the heating efficiency of the pump	$\frac{heat\ output\ delivered}{electric\ input\ to\ drive\ the\ pump}$
EER (Energy Efficency Rating)	Measure of the cooling efficiency of the pump	$\frac{cold\ output\ delivered}{electric\ input\ to\ drive\ the\ pump}$
SCOP (Seasonal Coefficient of performance)	Measure of the overall heating efficiency over a season	Interesting to understand how well the pump responds to temperature variations $\frac{heat\ output\ delivered\ over\ a\ season}{electric\ input\ to\ drive\ the\ pump\ over\ a\ season}$
SEER (Seasonal Energy Efficiency Ratio)	Measure of the overall cooling efficiency over a season Interesting to understand how well the pump responds to temperature variations	$\frac{cold\ output\ delivered\ over\ a\ season}{electric\ input\ to\ drive\ the\ pump\ over\ a\ season}$
Temperature difference at the condenser and evaporator	Measures the ability of the heat pump to extract heat from the heat source and transfer it to the load.	The higher the load temperature while remaining at the same district grid temperature the better $\frac{T°\ of\ the\ load\ leaving\ the\ HP}{T°\ of\ the\ source\ entering\ the\ HP}$
Global Warming Potential of the frigorific fluid	Measures the greenhouse effect of the frigorific gas	Inorganic Fluid (NH3, CO2, etc) ≈0 up to 10 HFC ≈ 1000 up to >2000 (under restriction of use) HFO < 1000 (under restriction of use)

Table 9: Heat pump characteristics

Ideal operating conditions of water/water heat pump correspond to that of LTDHC, which explains their wide use in this type of applications. They are also convenient because they can easily be adapted so that one HP can produce both hot and cold, reducing the energy loss.

Costs range from 0,5 €/MW up to 2 €/MW depending on the heating power and the application requirements.

- Typical performances

Central generation sized heat pumps can provide 50 – 500 kW of renewable heat per unit to a district heating network by harnessing energy from a low-temperature source. Domestic sized installations typically provide 5 – 40 kW.

Standard COP values for heat pumps are 4 kW heat / kW of electricity or above when used in a district heating network.

To provide ideal operating conditions, the heat source should be at a temperature of 15°C to 30°C, and the load should be supplied at a temperature around 40°C (and not above 65°C). Indeed, the heat exchange process is optimal when the temperature difference between the supplied and load water is not larger than 20°C.

- Ease of installation

Domestic size heat pumps require an expert technician for the installation but come as a single off-the-shelf product, only requiring correct plug & play. On the other hand, industrial size heat pumps used in district heating networks, can require several days of installation and will usually require specific engineering based on the requirements of the DH network.

Heat pumps collecting heat in open water loops (river water, some sea-bed) require additional design to take the changing environment such as the flow rate or the salt level of the water into account. These types of heat pumps also require civil works on the banks of the river/sea they are exploiting.

Apart from the river water source models, heat pumps usually require little maintenance.

3.2. Market overview

The heat pump market shows several interesting trends related to DHC:

- Sanitary hot water heat pumps (air-water) are the fastest growing segment across Europe. Sanitary hot water units combine a heat pump and a hot water storage tank. They are either sold as stand-alone units with the heat pump and the tank in one casing (skid system) or as systems combining a heat pump and a separate tank.
- Larger heat pumps for commercial, industrial and district heating applications are increasingly popular. They quite often use geothermal or hydrothermal energy. Air, water and ground can either carry renewable energy, or waste heat from processes.

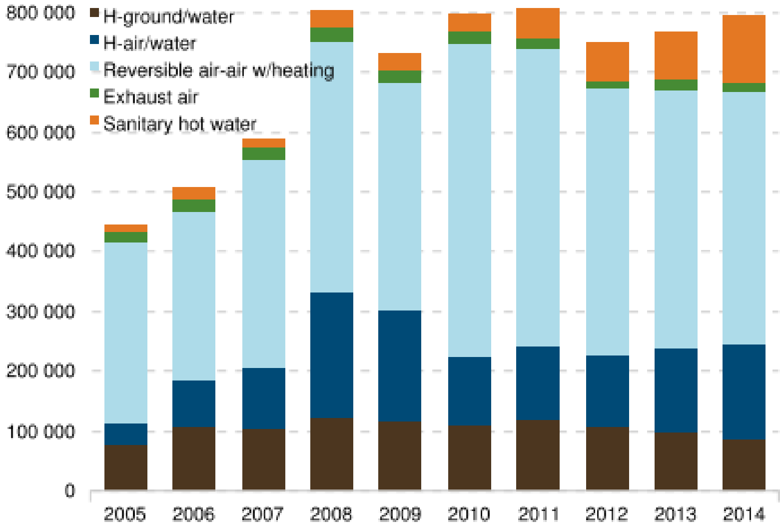


Figure 30: Evolution of yearly sales of heat pumps in Europe by category [46]

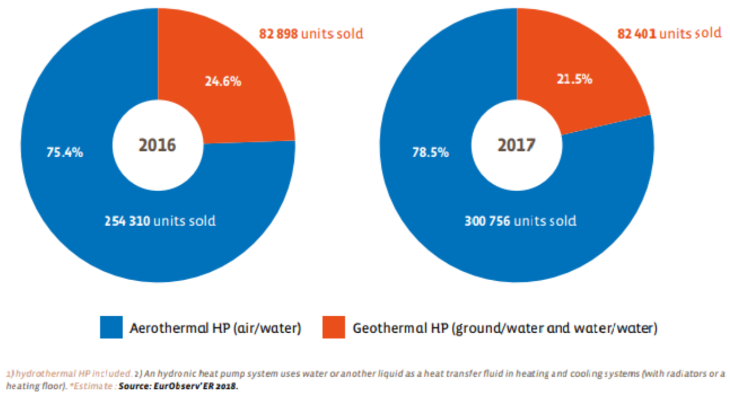


Figure 31 : Market share between geothermal and air-water heat pumps with hydronic system in 2016 and 2017 [44]

The first prototypes of heat pumps date back to the early 20th century and the first large scale installations to 1951. In Europe, there were 34.4 million heat pumps in operation in 2017, providing about 10.6 Mtoe in renewable energy.

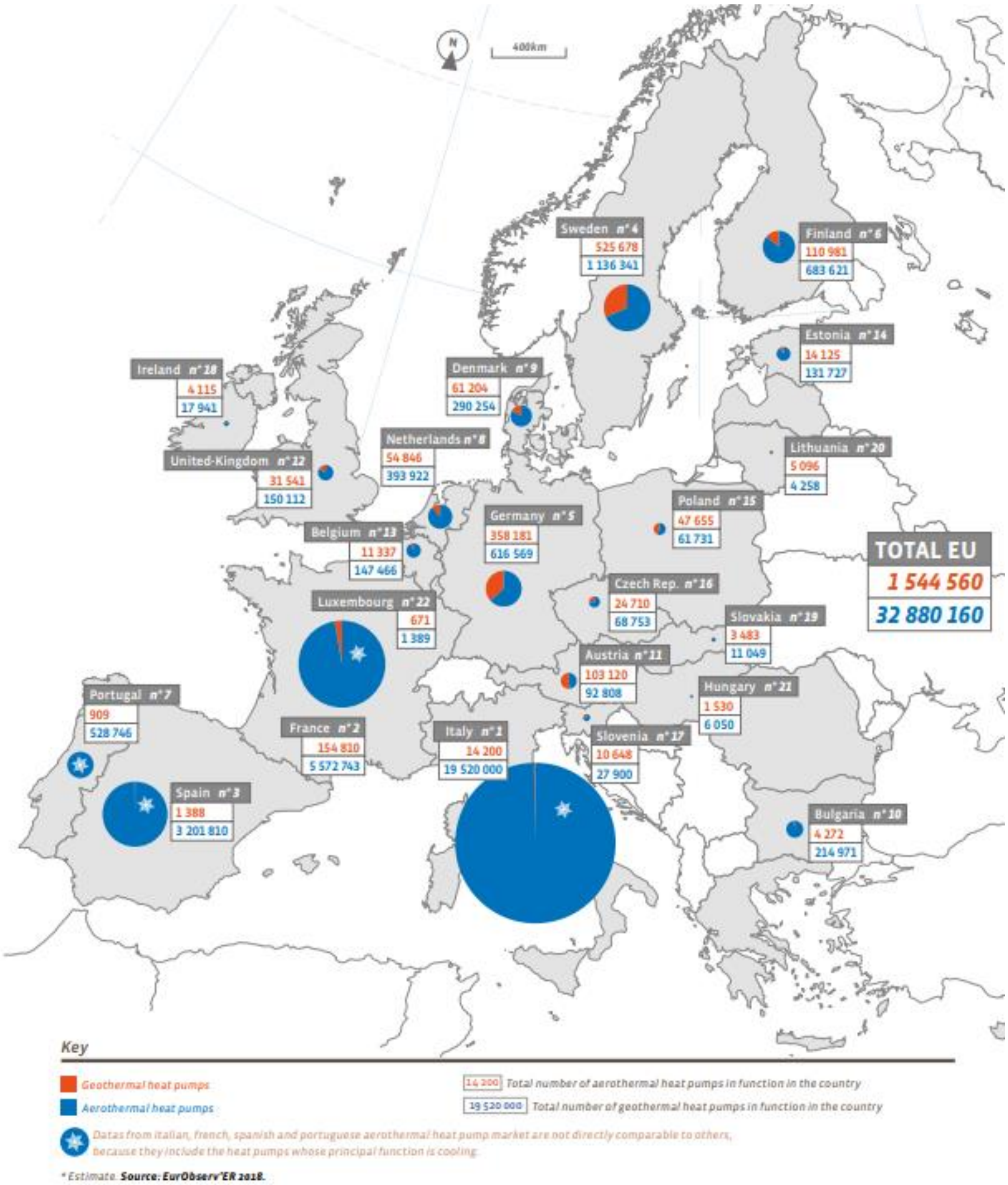


Figure 32 : Aerothermal and geothermal heat pump installations in operation in Europe in 2017 (installed units) [44]

When considering only geothermal heat pumps which are of interest for our study, Sweden and Germany are a far greater market. Furthermore, the new regulatory constraints on heating and cooling efficiency for new buildings makes it more and more difficult to use heat generation from fossil fuel, thus heat pumps become one of the more efficient alternatives.

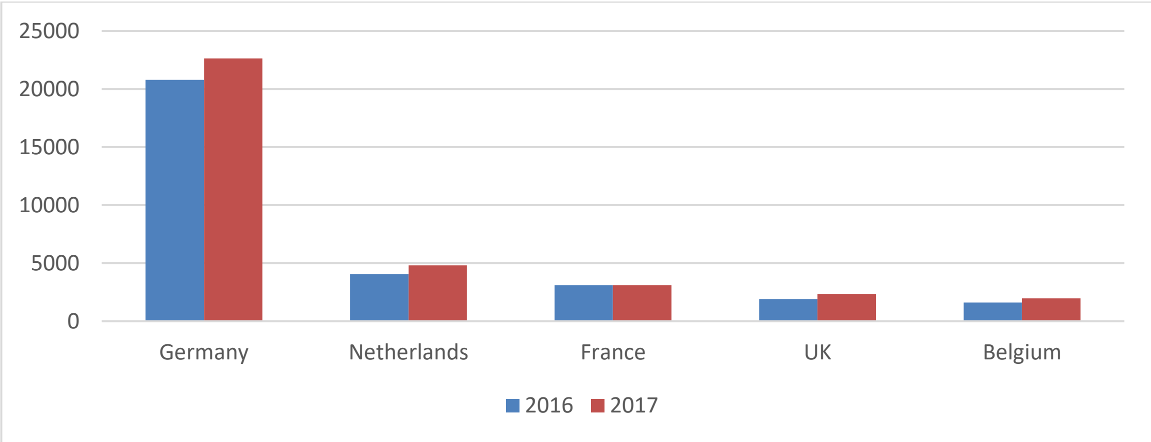


Figure 33 : Geothermal heat pumps unitary sales per country in 2016 and 2017 (hydrothermal heat pumps included). Data from [44]

France

France is one of the biggest markets for heat pumps; the electricity price is the lowest and subsidies are available for this technology. However, in France, reversible air-air heat pumps used for cooling represent the biggest part of the market and the geothermal market is quite small.

Germany

In Germany, air/air HPs are not included in the renewable energy targets. ASHPs (air/water HPs) were still the biggest market in 2017 and growing. Actually, the whole HP market has grown rapidly since 2015 in Germany due to new regulations in the building sector. The relatively low heating fuel and gas prices in Germany are a big challenge for HPs, but the new MAP incentive program and EnVE thermal regulation for buildings are expected to have positive impacts on the market.

UK

Though it is not performing as well as it was expected, the UK market has progressed by 18% in 2017 (total of 22 000 heat pumps installed, all categories included). The Renewable Heat Incentive provides an interesting subsidy towards the development of solar thermal energy, GSHPs, ASHP and biomass heat generation. This applies to both commercial (including district heating) applications and domestic installations. Additionally, the government intends to use heat pumps as an alternative to conventional oil-fired heating in the off-gas areas (3.9 M homes), as well as developing urban heat networks.

Netherlands

95% of domestic buildings in the Netherlands are gas heated. However, as part of its environmental actions, the government wants all residential buildings to be off-gas by 2050. Several big cities including Amsterdam have engaged in the procedure to disconnect the first gas networks over the next two years. The government expects that 30% of the heating requirements will be supplied by electric or hybrid heat pumps and 20% by district heating networks. Therefore, the Netherlands is expected to be a massive market for heat pumps.

Belgium

Heating & cooling represents approximately 52% (165 TWh) of the final energy demand in Belgium. Among these needs, 51% are for space heating and 38% for process heating. Currently, 46% of total residential heat is produced from gas and 36% from oil. There are very few district heating networks and the majority of heat pumps are in newly built residential areas [52].

3.3. Actors of the heat pump market

In terms of market maturity, it seems that consolidation is underway in Europe as there are now 9 major companies, owning 21 brands in 6 countries.

Groupe	Marque	Pays
BDR Thermea	De Dietrich	France
	Sofath	France
	Chappée	France
	Remeha	Pays-Bas
	Oertli Thermique	France
	Brotje	Allemagne
Bosch Thermotechnology	Bosch	Allemagne
	Buderus	Allemagne
Daikin Industries	Daikin Europe	Belgique
	Rotex	Allemagne
Atlantic	Atlantic	France
Nibe	Nibe Energy System	Suède
	CTC	Suède
	Technibel	France
	KNV	Autriche
Vaillant Group	Vaillant	Allemagne
	Saunier Duval	France
Viessmann Group	Viessmann	Allemagne
Stiebel Eltron	Thermia Heat Pumps	Allemagne
	Stiebel Eltron	Allemagne
Waterkotte	Waterkotte	Allemagne

Figure 34 : Location and parent companies of the main European heat pump brands [44]

For the purpose of industrialising DHC networks and to reduce costs, units should be available as standard production.

		France	UK	Netherlands	Belgium	Germany
Standard designs	BDR Thermea					
	Stiebel Eltron					
	Daikin					
	Climaveneta (Mitsubishi Electric)					
	Nibe					
	Bosch Thermotechnik					
	Stiebel Eltron					
	Carrier					
	Trane					
Tailor made designs	Friotherm					
	York					

Table 10: List of suppliers (data from manufacturer websites)

3.4. Trends and innovation

On one hand, the technical challenge of heat pumps is to maintain an efficient performance ratio while there is a big spread in temperature between the condenser and the evaporator. Research and innovation tend to work on this subject both for residential purpose (production of domestic hot water) and industrial purpose (need of high temperature for the processes).

On the other hand, the refrigerants used in these devices generate green-house gas emissions and are thus targeted by environmental laws, therefore a main field of interest is the deployment of "clean" refrigerants such as NH_3, CO_2, CH_4, C_3H_8.

- New refrigerants: CO_2 and ammonia

CO_2 heat pumps aim at producing hot water up to 90°C with an air source that could go under -5°C. The use of CO_2 as the refrigerant enables to maintain a good performance ratio despite the huge spread in temperature between the sink and the production.

Ammonia (NH_3) is considered as the best refrigerant for industrial applications. It cannot function at temperatures above 80°C. It does not contribute to the greenhouse effect. Though it is easily flammable, its strong odour enables to detect leaks easily.

- Hybrid power/gas heat pump:

Those air/air or air/water heat pumps use power and gas as energy sources. When the external temperature decreases and the air is too cold, the heat pump can calculate that the system is not energy efficient enough and switch to gas heating.

- Heat recovery in industrial processes

Heat recovery can be enhanced using a heat pump: it will enable an increase in the temperature of the recovery and thus allow a wider range of uses. As the recovery fluid is already at a medium temperature, the heat pump works at its best performance and usually has a COP ≥ 4.

The domestic heat pump market is currently mainly oriented towards new constructions: newer constructions have better insulation, making HPs a good candidate to provide domestic heat. Heat pumps are expected to gradually increase their share in the renovation market as well: their increased performance make them suitable for older buildings and solutions have been developed to couple HP to traditional boilers.

Various energy efficiency regulations in the building sector, as well as low-carbon electricity targets, both at a national and a European level, provide the right ecosystem for heat pumps development in Europe.

4. Coupling thermal and electricity grid

To date, very few DHC are coupled with electrical networks onto a whole Smart Energy Grid (SEG). In DHC, the electrical network is seen as a subsidiary utility (to fuel pumps, heat pumps, etc.) but not as a key energy vector. It is necessary to change this paradigm because the electrical network is linked to DHC in two major ways:

- Electricity is the main energy vector enabling the operations of all heat or cold generation equipment and enabling the distribution of thermal energy.
- Electricity and thermal energy are exchangeable through power to heat.

Thus, electricity must be included in the DHC sector transformation. Electrical renewable technologies will improve the share of renewables in DHC networks. Coupling vectors such as hydrogen and electrical storage will contribute to the flexibility of the system and will also enhance the use of renewables.

4.1. Renewable electric production

4.1.1. Solar PV

PV production has reached a mature stage, it thus has a key role to play in district heating and cooling. It should be stressed that this role can be played only if it is paired with the right heat production technologies.

PV installation can be on car park shade, roof mounted, ground mounted or even building integrated. Considering that DHC are mostly displayed in densely urbanized areas, building integrated PV may present interesting features. For DHC in rural areas or small urban areas, ground-mounted solar PV may have a key role to play. We can thus expect multiple decentralized power production from PV installations. In some cases, PV production will be operated by the same actors as the one that operate thermal production. In other cases, it will be different stakeholders and the system will need a third party or a smart contract to exchange electrical renewable production.

4.1.1.1. Description of technology

The solar PV market is currently dominated by crystalline silicon (c-Si) technology (93% market share), of which two types are used: monocrystalline and polycrystalline. Differences between technologies lie in the purity of the silicon: the purer the silicon, the better the efficiency. However, the increase in purity generates an increase in CapEx.

Monocrystalline

Monocrystalline PV panels are produced through the Czochralski process. It is a method used to obtain single crystals of silicon. This process leads to a silicon ingot, which is cylindrical in shape. This cylinder is then sliced into wafers, which are the basis for a photovoltaic cell.

Polycrystalline

Polycrystalline panels do not require the Czochralski process. Raw silicon is melted and poured into a square mold, which is cooled and cut into square wafers.

Thin-fim

Thin-film solar cells are manufactured by depositing extremely thin layers of photosensitive materials onto a low-cost backing such as glass, stainless steel or conductive plastic. The different types of thin-film solar cells can be categorized by which photovoltaic material is deposited onto the substrate:

- Thin-film amorphous silicon (a-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS/CIGS)
- Organic photovoltaic cells (OPC)

The market of thin-film modules grows at an exponential rate but remains at a low market share (7%).

Type	Monocristalline	Polycristalline	Thin-film amorphous
Applications	➢ Ground-mounted installation ➢ Roof installation ➢ Car park shed	➢ Ground-mounted installation ➢ Roof installation ➢ Car park shed	➢ Historically amorphous silicon was dedicated to small-scale applications: Watches, Calculator ➢ CdTe and CIS/CIGS now reach performances that enable to deploy them at medium scale
Advantages	➢ Best efficiency and specific power ➢ Best performance at low light condition ➢ Less performance loss at high temperature	➢ The process is simpler and costs less	➢ Any shape or size ➢ Simple mass production explaining low cost
Disadvantages	➢ The most expensive technology ➢ Waste of silicon in the process	➢ Low heat tolerance ➢ Lower performances	➢ Low efficiency rate
Efficiency	➢ 16 – 21%	➢ 13% to 17%	➢ 7% - 13%
Specific power	➢ 185 à 200 W/m²	➢ 170 W/m²	➢ 45 to 75 W/m²
Life time	➢ 25 years	➢ 25 years	➢ 10 – 25 years
Cost	➢ 1200 – 1600 €/kW	➢ 1 000 – 1400 €/kW	➢ 1 000 – 1400 €/kW
Main Manufacturers	➢ Sunpower ➢ Panasonic	➢ Sunpower ➢ Panasonic	➢ First solar ➢ Solar Frontier ➢ Sharp

	➢ Trina Solar / Yingli solar / Suntech – China ➢ LG Solar – South Korea	➢ Trina Solar / Yingli solar / Suntech – China ➢ LG Solar – South Korea	

Table 11: panel technical card

4.1.1.2. Market overview

The global PV market has grown rapidly in the last decade. Cumulative global installed PV capacity grew from 6,1 GW at the end of 2006 to 398 GW at the end of 2017. From 2010 to 2016, net additions grew about 28% annually on average. Recent growth in the Asian PV market (China and Japan) has more than compensated for the decrease in new capacity additions in Europe in recent years.

Over the next years, solar PV is expected to lead renewable electricity capacity growth, expanding by almost 580 GW according to the IEA market analysis and forecast from 2018 to 2023 on renewable energy and technologies, “Renewables 2018”. According to the IEA, PV will provide around 5% of global electricity production by 2030 and 11% in 2050 and avoid 2.3 Gt of CO2 emissions per year and will reach grid parity by 2020 in many regions.

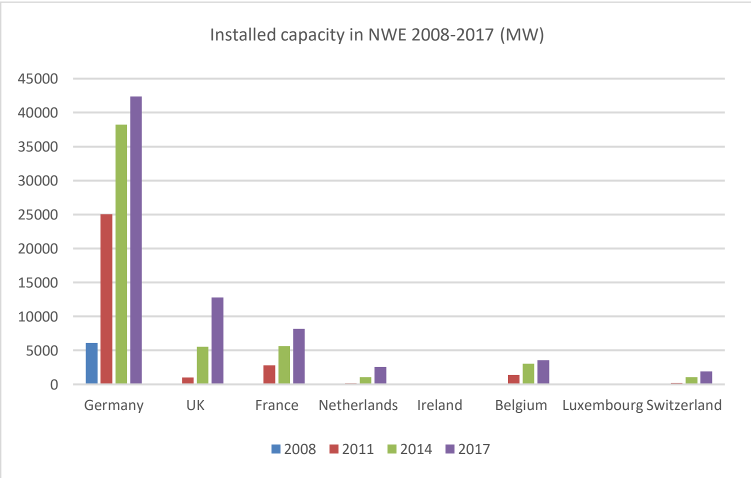


Figure 35: Cumulative Grid connected capacity [56]

According to the Global Market Outlook for Solar Power 2018-2022 by SolarPower Europe, the European total solar PV installed capacity is expected to reach between 164,9 GW (low scenario) and 269,4 GW (high scenario) by 2022.

Indeed, PV is expected to grow very strongly in NWE during the next few years for several reasons:

- EU 2020 targets encourage countries to increase their renewables share and reduce their CO_2 emissions.
- Solar tendering tools have highlighted the low cost of solar power and are being chosen by several European countries over feed-in tariff schemes.

- Solar is much cheaper than retail electricity in most NWE countries, which encourages people and companies to invest in self-consumption solar projects. The quickly falling costs of energy storage systems and the improvement of smart energy systems encourage self-consumption.

4.1.1.3. Current prices and expected evolution

Most of the installation costs are driven by the price of the module. In Europe, providers can source their modules at the cheapest price (mostly from China) but the cost of the global installation will still be different. The differences will depend on:

- Domestic market maturity
- Local labour price
- Cost of grid connection

The average price in 2016 for European countries ranged from 1000$/kW in Germany to 1400$/kW in the UK.

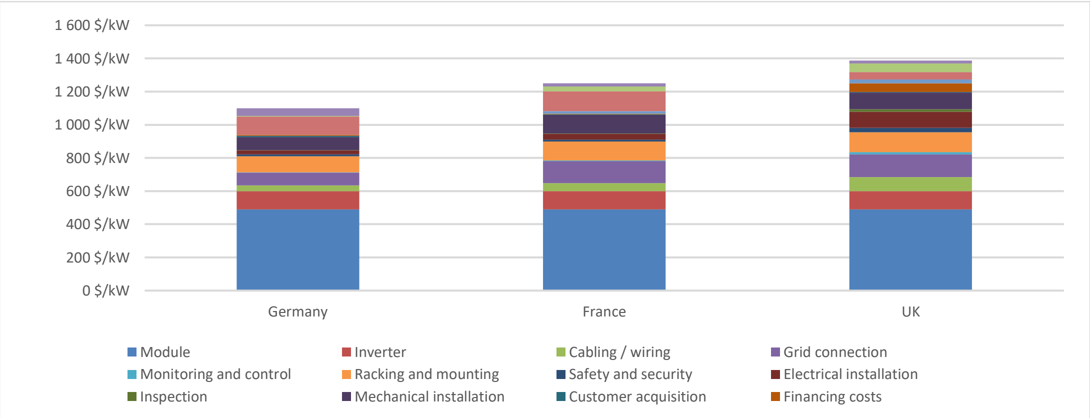


Figure 36: Total Installed cost [56]

- Expected evolution in prices

Solar PV module prices in Europe decreased by 83% from the end of Q1 2010 to the end of Q1 2017. In recent years the cost reduction is slower as PV module manufacturers made efforts to return profit margins to more sustainable levels.

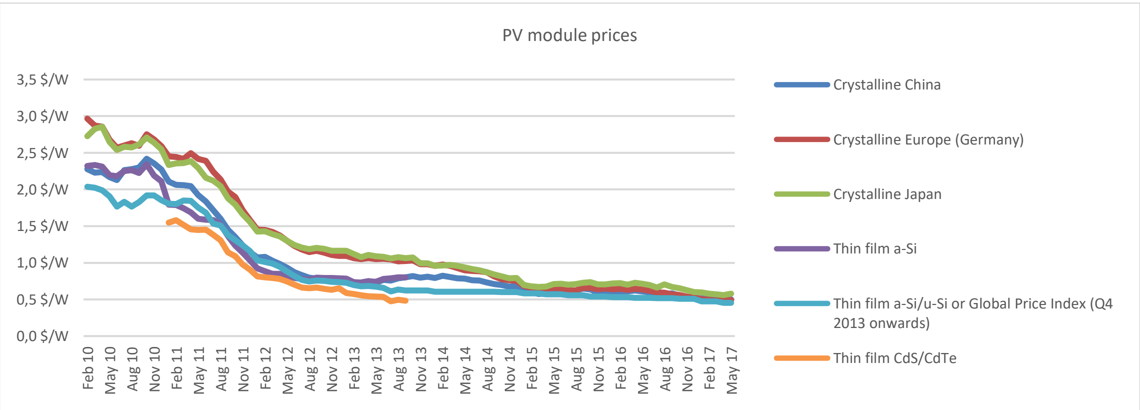


Figure 37: PV modules price evolution (data from GlobalData)

While a decrease remains likely on the module prices, the other costs (except for the inverter) are not expected to decline.

4.1.1.4. Technical challenges and innovation

➢ Increase in performance of standard crystalline modules

The increase in performance is mainly explored through two aspects: the deployment of silicon surface covered with a nanostructured surface layer to boost the light absorption properties and the reduction of the light induced degradation.

➢ Development of thin-cells to deploy solarization on various objects

One of the main obstacles to solarization is the seek for available area that does not compete with any other economic activity. The weight issue is addressed through the deployment of thin-cells modules that tend to reach a weight inferior to 10 kg/m² (some are already at 500g/m²) vs 15-20 kg/m² for a standard panel. These technologies can thus be deployed massively on many objects (boats, walls, cars, etc.).

➢ Floating solar panels to answer a lack of land

The first large scale water floating installation was built in Japan in 2013. The world now counts around 300 MWp of floating installations mostly in Japan (66%) – [Rest of Asia: 21%; Europe: 11%; USA: 2%]. Floating solar panels try to respond to a lack of land when rooftops and ground-mounted installation cannot be an option. Floating PV is deployed in the following conditions:

- No use of valuable land; or high cost of valuable land
- Conflict with agricultural uses

The most common water surfaces deployment is: retention pond, dam, former mining lake.

In Europe, the deployment is restrained by the installation cost which is 20% higher than a standard installation.

Figure 38: Floating panels installation

4.2. Electrical storage

Electricity storage consists in storing energy under various forms, when there is an overproduction of electricity, in order to then generate electricity when there is insufficient production compared to the demand.

Electrical storage will improve the integration of variable renewable electricity in district heating and cooling models.

4.2.1.Technical description

Three big families of electrical storage technologies can be distinguished: Electro-chemical, Electro-mechanical (including Pumped Hydro Storage) and electrical storage (magnetic or static).

there are a wide variety of renewable energy-specific applications for electrical storage, which account for almost half (49%) of all main capacity applications.

When it comes to evaluating storage technologies, the following technical parameters are studied and compared:

Feature	Description
Energy-to-power ratio	Relationship between energy capacity and power capacity in a given application. (kWh/kW)
Number of charge cycles	The number of complete discharging and charging of a storage system before failure or before significant capacity loss.
Depth of discharge	The ratio of discharged energy (kWh) to usable capacity (kWh). (%)
Round-trip efficiency	The ratio of energy output (kWh) to energy input (kWh) of a storage system during one cycle. (%)
Energy density	The nominal battery energy per unit volume (kWh/L).
Power density	The maximum available power per unit volume (kW/L).

The best use cases for a technology are then determined based on the above parameters. Figure 39 gives an overview of the main specifications by type of technology, for example:

- Electro-mechanical storage (PHS and Compressed Air Electrical Storage) are large scale technologies, that do not respond quickly to solicitation and are thus exploited as an alternative power supply for grid support. They have a low power and energy density that only allow specific feasibility cases.
- Fly-wheels have an intermediate scale capacity ranging from 100 kW to 10 MW and are operated for power quality thanks to their short response time.
- Electrochemical batteries range from small power (1kW) to medium power (10 MW) – mainly by addition of small units - and have a moderate response time, making them suitable for power quality services as well as power supply. The advantage of Li-Ion compared to Lead-Acid lies mainly in the higher energy density ratio.

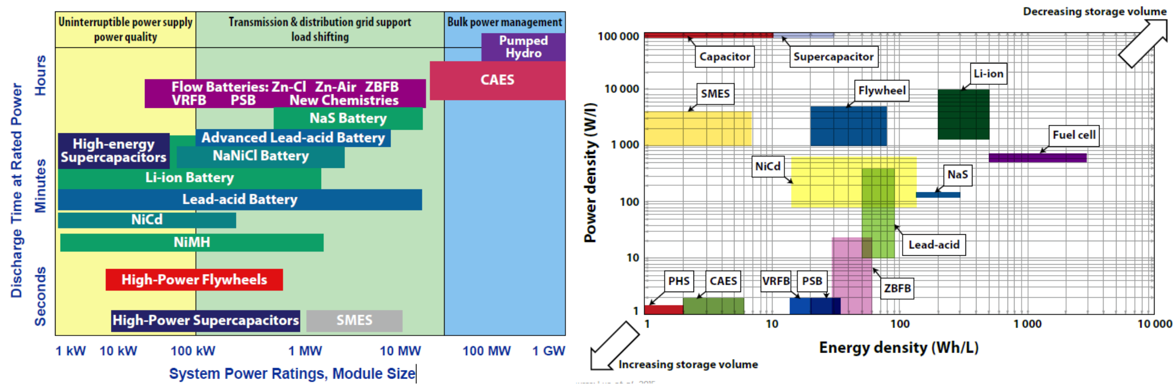


Figure 39: Power rating and discharge time comparison (left) – Energy density and power density (right) [58]

Acronyms: *Superconducting Magnetic Energy Storage (SMES); Lithium-Ion (Li-ion); Nickel-Cadmium (NiCd); Sodium-sulfur (NaS); Pumped Hydro Storage (PHS); Compressed Air Electrical Storage (CAES); Vanadium Redox Flow battery (VRFB); Poly sulfide Bromide battery (PSB); Zinc Bromine Flow battery (ZBFB); Nickel Metal Hybrid Battery (NiMH)*

4.2.1.1. Main characteristics

Type	Lead-acid	Li-ion	Flow batteries	High temperature sodium sulfur	Flywheel
Applications	➢ Uninterruptable power supply system ➢ Solar home system in off-grid application ➢ Traction battery (forklift, golf-carts) ➢ Communication towers in rural areas ➢ Starter batteries in car	Wide variety of applications: ➢ Electromobility ➢ Portable Applications ➢ Stationary storage devices from several kW (residential applications) to several MW (renewable production scale): time of bill use management and renewable firming.	➢ To date, 49 MW of installation are operating for: ○ Frequency regulation ○ Renewable capacity firming ○ Renewable generation shifting	➢ Electric bill management ➢ Energy time shifting ➢ Frequency regulation	➢ Uninterruptable power supply applications ➢ Frequency or voltage regulation ➢ Power buffering for tram and underground trains
Advantages	➢ Low cost ➢ Ample manufacturing and operational experience	➢ High power and energy density ➢ High rate and power discharge ➢ High round-trip efficiency	➢ Can operate close to ambient temperature ➢ Independent scaling of energy and power characteristics	➢ high energy density, ➢ non-toxic materials ➢ low self-discharge rate	➢ Fast charge capabilities ➢ Long life cycle ➢ Wide operational experience ➢ High power density
Limitations	➢ Heavy ➢ Low energy density ➢ Does not respond well to deep discharge (optimal discharge rate limited to 50%) ➢ Lead toxicity ➢ Loss of acid water (flooded battery) requires maintenance	➢ Thermal instability, overheating and release of oxygen ➢ Impact of temperature on lifetime ➢ Cooling the battery storage is often necessary ➢ Power loss below 0°C	➢ Risk of leaks of acid fluids ➢ Complex system architecture => higher operation and maintenance cost	➢ high annual operating cost, which can be USD 40-80/kW/year, mostly for heating. ➢ Corrosion issues are a major ageing mechanism of high temperature cells.	➢ Low energy density ➢ Security issues because of high velocity rotation ➢ Size and weight of containment vessel
Cost	➢ 100 $/kWh – 500 $/kWh	➢ 200 $/kWh – 840 $/kWh	➢ 400 - 1 600 $/kWh	➢ 270 $/kWh - 735 $/kWh	➢ 2 000 - 6 000 $/kWh
Trends	➢ Hybrid system with flywheel ➢ Prevent sulphation with high-surface carbon layers ➢ Copper Stretch Metal to improve the performance	➢ Integrate and optimize thermal management ➢ Scale manufacturing improvement to decrease prices ➢ Research on high voltage electrolytes	➢ Improve membrane resistance ➢ Salt water electrolyte	➢ Corrosion prevention ➢ Lowering temperature for the electrolyte exchange	➢ Reducing self-discharge rate ➢ Rotor design

Table 12: Main characteristics of electrical storage technologies

4.2.1.2. Performances

Type	Lead-acid	Li-ion	Flow batteries	High temperature Sodium sulfur	Flywheels
Round trip Efficiency	➢ 70% to 90%	➢ 92%-96%	➢ 70%	➢ 80%	➢ 85%
Depth of discharge	➢ 50% - 60%	➢ 80% - 100%	➢ 100%	➢ 100%	➢ 75 - 90%
Energy intensity	➢ 50 Wh/L to 100 Wh/L	➢ 200 Wh/L - 735 Wh/L	➢ 10 to 80 Wh/L	➢ 140 Wh/L - 300 Wh/L	➢ 10 - 200 Wh/L
Cycle life	➢ 2 500	➢ 5 000 – 10 000	➢ > 10 000	➢ 5 000	➢ > 1 000 000
Life time	➢ 5 - 20 years	➢ 5 – 20 years	➢ 5 t- 20 years	➢ 10 - 25 years	➢ 15 - 35 years
Power range	➢ 1 kW - 1 MW (by addition of small kW units)	➢ 1 kW - 1 MW (by addition of small kW units)	➢ 50 kW - 50 MW	➢ 1 – 10 MW	➢ 10 kW - 20 MW

Table 13: Main performances of electrical storage technologies

4.2.2.Market overview

Nowadays electrical storage is a technical asset of smart energy grids that enable power supply instead of the electrical grid. The battery must have been previously filled by a solar PV production or by the grid itself with lower prices. The same concept can be use in 5GDHC where solar production can fill the battery with a production surplus. There are several examples of this usage in smart grids such as in "Nice Grid" in France where consumers have electrical storage for their specific consumption. It enables them to manage their bill and prevents grid consumption during peak of demand. Nevertheless, there is no known current demonstrator in district heating and cooling scheme.

4.3. Hydrogen

Hydrogen has a key role to play in 5GDHC because of its specificity as a coupling energy vector. It can be used both for direct injection in the gas network, thus substituting a share of fossil fuel, and in the electrical network thanks to a fuel cell. While nowadays, over 95 % of hydrogen production is fossil-fuel based, renewable energy-based production is expected to grow in the coming years.

In 5GDHC, hydrogen will be used for:

- Injection into existing natural gas grids up to a certain share, thereby reducing natural gas consumption and emissions for heating systems.
- Large scale storage media from renewable production (electrical production, gasification), allowing seasonal storage

The most established technology options for producing hydrogen from renewable energy sources are water electrolysis and steam reforming of biomethane/biogas.

4.3.1.Hydrogen as an electricity vector

An electrolyser is a device that splits water into hydrogen and oxygen using electricity. When electricity produced from renewable energy sources is used, the hydrogen becomes a carrier of renewable energy.

Proton exchange membrane (PEM) electrolysers and fuel cells are approaching technical maturity and economies of scale. Commercial deployment has started in several regions of the world (e. g. Japan, California, Europe).

4.3.2.Hydrogen storage

Hydrogen as an energy carrier has by far the highest gravimetric energy density. The mass-based energy density of hydrogen is thus almost three times higher than that of liquid hydrocarbons, however, the volumetric energy density of hydrogen is comparatively low. Therefore, for practical handling purposes, the density of hydrogen must be increased significantly for storage purposes.
The most important hydrogen storage methods, which have been trialled and tested over lengthy periods of time, include physical storage methods based on either compression or cooling or a combination of the two (hybrid storage). In addition, many other new hydrogen storage technologies are being pursued or investigated. These technologies can be grouped together under the name materials-based storage technologies. These can include solids, liquids or surfaces.

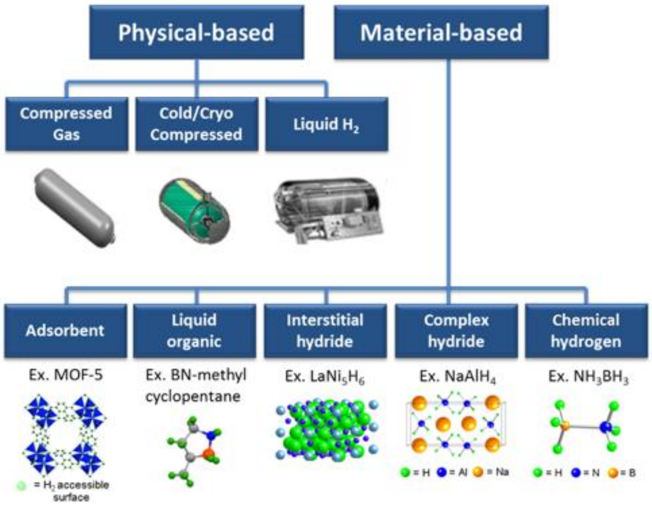


Figure 40: Different typologies of hydrogen storage [60]

There are different technologies of hydrogen storage mostly depending on the pressure of the system.

4.3.2.1. Liquified Hydrogen

In addition to storing gaseous hydrogen under pressure, it is possible to store cryogenic hydrogen in the liquid state. Liquid hydrogen (LH2) is in demand today in applications requiring high levels of purity, such as in the chip industry for example. As an energy carrier, LH2 has a higher energy density than gaseous hydrogen, but it requires liquefaction at –253 °C, which involves a complex technical plant and an extra economic cost. Tanks for LH2 are used today primarily in space travel.

4.3.2.2. Cold- and cryo-compressed Hydrogen

In addition to separate compression or cooling, the two storage methods can be combined. The cooled hydrogen is then compressed, which results in a further development of hydrogen storage for mobility purposes. The first field installations are already in operation. The advantage of cold or cryogenic compression is a higher energy density in comparison to compressed hydrogen. However, cooling requires an additional energy input.

4.3.2.3. Materials-Based h2 Storage

An alternative to physical storage methods is provided by hydrogen storage in solids and liquids and on surfaces. Most of these storage methods are still in development, however. Moreover, the storage densities that have been achieved are still not adequate, the cost and time involved in charging and discharging hydrogen are too high, and/or the process costs are too expensive.

4.3.2.4. Underground Storage

When it comes to the industrial storage of hydrogen, salt caverns, exhausted oil and gas fields or aquifers can be used as underground stores. Although being more expensive, cavern storage facilities are most suitable for hydrogen storage. Underground stores have been used for many years for natural gas and crude oil/oil products, which are stored in bulk to balance seasonal supply/demand fluctuations or for crisis preparedness.

To date, operational experience of hydrogen storage caverns exists only on a in a few locations in the USA and Europe. In particular, the underground natural gas stores in Europe and North America could potentially be used as large reservoirs for hydrogen generated from surplus renewable energies.

4.3.3.Power to gas

The injection of hydrogen from renewable power into the gas grid represents a potential revenue for hydrogen's economics and an additional way to increase renewable share in the energy consumption. Hydrogen can be blended with natural gas and injected into the gas grid, up to certain levels.

Existing studies show that, for district heating and cooling objects (gas, turbine, gas boilers) at low concentrations (up to 10–20 % in volume), blending may not require major investment or modification of the infrastructure.

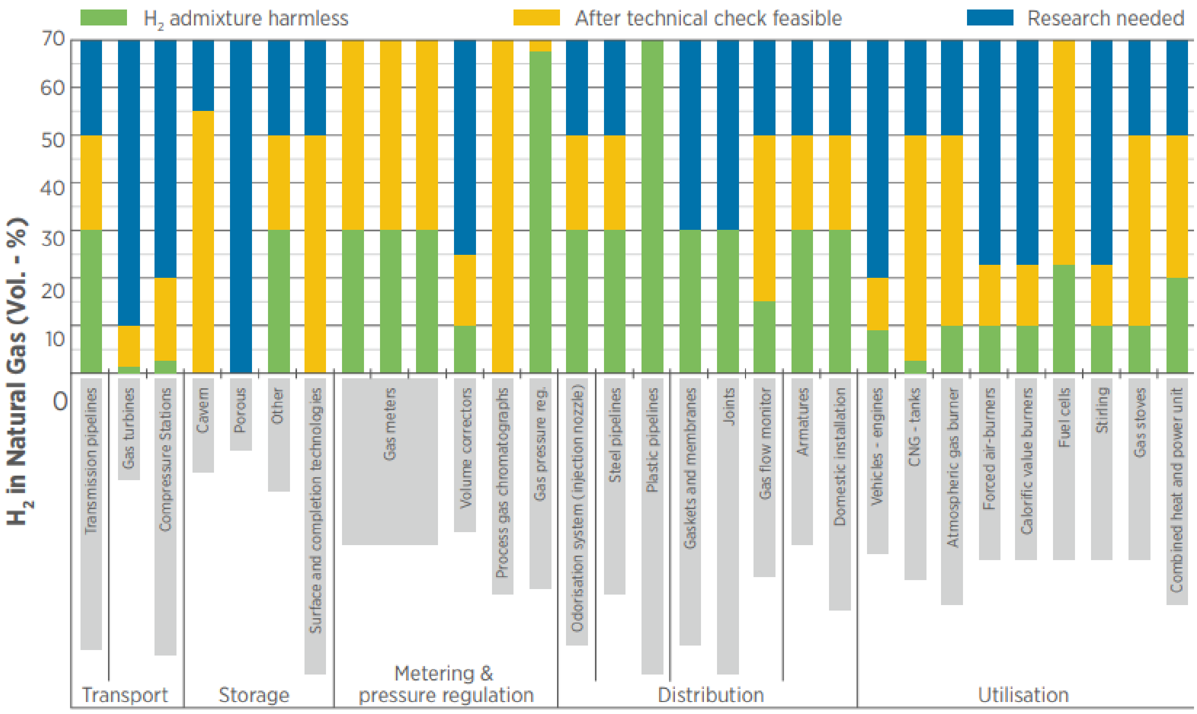


Figure 41: Hydrogen tolerance of gas infrastructure and uses [64]

4.3.4.Market overview

Currently, hydrogen is used in Europe through direct injection into the natural gas network thanks to several pilot installation (France hase two pilots Dunkerque and Fos-sur-mer). It thus enables substitution of natural gas consumption (and GHG emission) to hydrogen.

Some hydrogen CHP exist in the the USA and South Korea, but they are fueled by hydrogen produced by fossil fuel. Whereas the technology is interesting and mature (fuel cell producing both heat and electricity) hydrogen must be sourced from renewables to be deployed in 5GDHC.

Conclusion

5^{th}GDHC networks bring lots of positive outcomes, be it through economies in overall necessary heat production, using more renewable heat production methods, or being part of an integrated energy system.

One can see that the technologies required to scale up 5^{th} GDHC are mostly all mature, which makes it a technically accessible technology.

Interseasonal and daily/weekly thermal storage shall be an essential piece of the puzzle, and unfortunately is one of the least mature. Therefore, it is essential for the development of 5^{th}GDHC to correctly map interseasonal storage potential at the city/neighbourhood level.

As presented in the first chapter, 5^{th}GDHC networks rely on 2 thermal loops: one delivering heat, the other delivering cold. This enables a balance of heating and cooling needs of the users. The optimization of the balance will however require a significant range of user types being connected to the same network (cooling demand from retail or datacentres, heating demand from residential or tertiary buildings). If this can be achieved, 5^{th}GDHC will be bring a serious additional value compared to 4^{th}GDHC, which are currently not well suited to provide true local heat to large cities.

Yet, due to its requirement for additional heat/electricity sources, 5^{th}GDHC networks currently require additional investments, and are not well known by investors. Therefore, to unlock the large potential in carbon footprint reduction promised by 5^{th}GDHC, it is crucial that the whole value chain mobilizes to spread knowledge about these circular heating systems.

As stated in introduction, the D2Grids project aims at mobilizing the value chain in North Western Europe and shall target 4 objectives. The first one is to ensure that equipment manufacturers and service providers deliver suitable elements for 5^{th}GDHC. This report is part of this target and has grasped a first shot of the current state of technology and their future challenges. The next phase shall work on the interactions between all stakeholders in order to make sure that knowledge is shared and accessible to all, thus ensuring suitability of equipment and services provided.

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