White Paper on Clean Heating & Cooling Technologies and Thermal Energy Storage for Buildings

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Contents

List of acronyms

BIM	Building Information Modeling	IEQ	Indoor Environmental Quality
CHP	Cogeneration of Heat and Power	IWG5	Implementation Working Group 5 on Energy Efficiency in Buildings
CCHP	Cogeneration of Cooling, Heat and Power	LiBr	Lithium Bromide
DH	District Heating	NECPs	National Energy and Climate Plans
DHC	District Heating & Cooling	PCMs	Phase Change Materials
DHW	Domestic Hot Water	PTES	Pit Thermal Energy Storage
EC	European Commission	PVT	Photovoltaics (PV)-Thermal (T)
ECTP	European Construction and sustainable built environment Technology Platform	RES	Renewable Energy Source(s)
EPBD	Energy Performance of Buildings Directive	RHC ETIP	European Technology & Innovation Platform on Renewable Heating & Cooling
EU	European Union	SET Plan	(European) Strategy Energy Technology Plan
GHG	Greenhouse Gas	TCMs	Thermochemical materials
GWP	Global Warming Potential	TRL	Technology Readiness Level
HVAC	Heating, Ventilation and Air Conditioning	TES	Thermal Energy Storage

Executive Summary

The built environment is responsible for 35% of the greenhouse gas emissions and 85% of the buildings in Europe are older than 25 years. It is therefore a big task to reach a 100% renewable heated and cooled built environment. This White Paper describes how clean heating and cooling technologies and thermal energy storage can enable the uptake and utilisation of renewable energy and be integrated seamlessly in all buildings. The technologies concerned are heat pumps, solar thermal energy technologies, thermal storage, micro-cogeneration, and district heating & cooling.

For every technology, the present state of development and market maturity is introduced, and a short inventory made of the barriers to further implementation. Targets are formulated that can help to define further research, development and demonstration programmes and topics and can aid in tracking the progress.

For heat pumps, that already supply a considerable part of the buildings with heating and cooling, work is to be done in guaranteeing a safe and efficient operation, in novel technologies to supply heat at higher temperatures, in smart control systems and in the further simplification of the installation process.

District heating and cooling has clear advantages in densely populated areas and has large growth opportunities. Developments are needed in increased flexibility, increase the share of renewable energy sources that feed into the systems, in developing skills and qualifications of the work force, in increased flexibility and digitalisation and in enhanced policies supporting the expansion of district heating and cooling systems.

Micro cogeneration of cold, heat and power can provide the three energy forms in an effective, distributed way. The technologies must be adapted to the switch from fossil fuels to renewable fuels. Flexible, dual fuel technologies for either gaseous of liquid fuels are needed, and the operational concepts should be flexible, playing an increasingly important role in distributed, flexible sector coupling.

Thermal energy storage technologies offer flexibility and an increased use of intermittent renewable energy sources, from the single household scale to the district heating grid scale. In general, with the transforming energy landscape, novel business cases for thermal energy storage are needed. Technology development needs are broad, resulting from the large variety of thermal energy storage technologies: storage material improvement from a basic science to applied level, component development, system integration, interface standardisation, experts network development, training programs and further demonstration to accelerate the uptake of novel technologies and applications.

Solar thermal and PVT technologies are increasingly applied to provide heat and electricity on a local but also district scale. Work is needed to further reduce the cost by pre-fabrication and plug-and-play solutions, and to find standardised solutions for easier integration, especially in building renovation.

A significant challenge arises from the variety of clean heating and cooling technologies used in buildings. The integration and combination of these technologies pose development challenges in the areas of defining appropriate sets of assessment parameters, in smart system design using building information models, in the implementation of life cycle assessment techniques, in realising guidelines for safety, energy efficiency and sustainability, in practical cost-benefit analysis methods and in the creation and use of open databases enabling the further use of digital tools from design to operation and maintenance.

These areas are not isolated, and attention is also needed for other areas that are coupled to clean energy technologies and thermal energy storage in the built environment: measures to decrease the energy consumption of buildings through novel building materials and better design and construction of buildings; the coupling with other elements of the energy systems like industry and mobility; social acceptance and legal aspects and of course financial aspects. These external areas are partly covered by other white papers of the Implementation Working Group 5 and partly by the activities of other SET Plan elements.

1. Introduction

Realising a 100% renewable heating and cooling in the European built environment is a grand task. First, there is the complexity of integrating novel clean technologies in the building stock, as, according to official EU sources, 85% of EU building stock is prior to 2000, and only a quarter of them have a proper energy performance[1]. Second, the heating and cooling services (DHW and room heating & cooling) represent 35% of energy related GHG emissions in 2021[2], while domestic heating is responsible for 53% of fine particulate matter pollution[3]. Clean heating and cooling technologies and thermal energy storage should enable the uptake and utilisation of renewable energy and be integrated seamlessly in the buildings.

In the last decade, a comprehensive legal and policy framework boosted the development, deployment, and smart energy management of clean heating & cooling technologies, as well as inclusion of renewable energy, through Energy Transition and Decarbonisation. Some of the instruments that comprise this framework are the **Energy Performance of Buildings Directive** (EU/2010/31) as part of the **Clean Energy for All Europeans package**; the **Renovation Wave** strategy, within the **European Green Deal**; the **Fit for 55 Package**, including the **Social Climate Fund**. The **REPowerEU plan** also highlighted the necessity of addressing the EU's building stock to reduce reliance on foreign energy sources.

From the industry, further initiatives arose, such as the **EU's industrial strategy,** to advance on sustainability and digitalization while boosting global competitiveness and strategic autonomy, by green investments, as have the **Recovery and Resilience Facility**, the **Green Deal Industrial Plan** and the **National Energy and Climate Plans (NECPs).** The **European Construction and Sustainable Built Environment Technology Platform (ECTP)** developed a **Strategic Research and Innovation Agenda (SRIA)**, identifying Research and Innovation (R&I) priorities. Concerning clean heating & cooling technologies and thermal energy storage, those priorities focus on realising affordable, modular, and user-centric solutions for renovating existing buildings to be more energy-efficient and low-carbon, integrating renewable energy sources and smart technologies, prioritizing scalability, and adaptability. The **European Technology & Innovation Platform on Renewable Heating & Cooling (RHC-ETIP)** also contributes through a common baseline to boost the technologies and their energy transition.

The ECTP and RHC-ETIP work, together with the *Contribution by the Implementation Working Group 5 to the European Commission's upcoming "Heat Pumps Action Plan to accelerate roll-out across the EU*, and the International Energy Agency (IEA) report entitled *"The future of Heat Pumps",* constitute the origin of this White Paper.

This White Paper, issued by the Implementation Working Group 5, Task Force 3 on Clean Heating & Cooling Technologies, and Thermal Energy Storage, aims to advancing those

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[1] https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

[2] Greenhouse gas emissions from energy use in buildings in Europe | European Environment Agency's home page (europa.eu)

[3] https://epha.org/wp-content/uploads/2022/03/epha-position-paper-clean-heating.pdf
https://www.eea.europa.eu//publications/europes-air-quality-status-2024

technologies, focusing on heat pumps, solar thermal energy technologies, thermal storage, micro-cogeneration, and district heating & cooling. The White Paper will be in support of the upscaling of the TRL of the above-mentioned technologies, demonstrating them in real environments and bringing them to the market. It shows the way to achieve this purpose and detect the main hurdles, also providing smart targets and actionable strategies and initiatives to face them.

A thorough grasp of current challenges can significantly help researchers, professionals, policymakers, and business players. This study delves into the evolution, obstacles, and prospects of clean and cross-cutting heating & cooling technologies and thermal energy storage, setting goals and suggesting steps forward. It serves as a valuable guide for the heating and cooling sector, ultimately shaping a future marked by energy-efficient, sustainable, and financially sound buildings.

This paper is divided into two main parts. The main chapter describes the technologies in short, providing an overview of the technology landscape, the level of development and the main applications per technology. In chapter 4, the gaps and barriers for every technology are shortly described, targets are defined and activities that lead to a proper implementation of the technologies are shortlisted.

2. Technologies for clean heating and cooling and for thermal energy storage

One of the main challenges of housing is guaranteeing a comfortable indoor environment. To this purpose, a combination of passive and active measures must be adopted: passive measures are linked to the design of buildings and the choice of construction materials, and active measures consist of clean heating and cooling technologies. These technologies include the local conversion of renewable energy, the storage and conversion of heat or cold and the distribution of these to the different parts of the building. They are clean when they exclusively use renewable energy. They are designed considering the basics of circularity, and minimal use of materials, although this requirement will not be further used for identification of the technologies.

The White Paper includes technologies applied in buildings, be it single buildings, collective housing, commercial or public buildings or building complexes. Moreover, it includes technologies enabling the interaction with a district heating or cooling network.

In the following paragraphs, a short description of the considered clean heating and cooling and thermal energy storage technologies for buildings will be given.

Solar thermal and PVT

Solar thermal technology converts solar radiation into heat or power. There is a range of different technologies on the market, from flat plate collectors, vacuum tube collectors, concentrators of solar radiation to a smaller surface, line, or point, generating higher temperatures for industrial or power generation purposes, and commonly using water as heat transfer fluid. Closely connected to solar thermal is photovoltaics-thermal or PVT technology, that generates power and heat by combining solar PV and thermal technologies in one panel.

Solar thermal systems for buildings offer a mature and efficient solution towards sustainable and energy-efficient domestic hot water, heating, and cooling solutions, when combined with certain technologies (such as chillers). The scope for these systems is vast. With advancements in technology, supportive policies, and integration into sustainable building and a combined energy system, solar thermal systems can play a crucial role in reducing carbon footprints, saving energy costs, and enhancing energy security.

Solar district systems may supply domestic hot water, heat, cold, and power to communities and urban areas using solar thermal energy. They have seen increasing adoption, particularly when there is a stronger push for decarbonising the heat supply to DH networks.

Solar thermal water heating for single-family houses is a mature and cost-effective solution. In warmer climates, thermosiphon systems are a well-developed solution, supplying 100% of the needs by means of over 90% solar fraction and the rest covered by an integrated backup. For forced circulation systems, with the thermal storage inside the house, the dependency from the backup is higher and the challenge is therefore to develop robust, plug-and-play and cost-efficient package solutions. New solutions, such as PVT, radiative and evaporative passive cooling are promising with growing deployment.

Heat pumps

Heat pumps transform low-temperature heat into a higher-temperature heat. The process is driven either by electricity in mechanical compression heat pumps or in several novel heat pump technologies, or by heat in sorption heat pumps. The state-of-the-art is given by compression heat pumps, using an electric compressor to increase the pressure of a working fluid, and driving it through a circuit consisting of a condenser at the hot side, a pressure reduction valve, and an evaporator at the cold side. With sorption heat pumps, the active medium is charged in a low-pressure state by an external generation heat source, then discharged in a higher-pressure state to supply the heat at a higher temperature level.

There are several heat pump technologies at a lower technology development level, like thermoacoustic, thermoelectric, and magnetocaloric. Some of them have potential better performance or a higher temperature increase potential. The challenges in the maturing of these technologies depend on and lie in the development of materials, components and first demonstrators and production technology.

Large-scale heat pumps can harness waste heat sources – from data centres, wastewater treatment plants, metro stations, and other industrial and tertiary activities – to reach higher efficiencies and supply sustainable heating to many households via district heating networks. Large-scale heat pumps are also excellent to harness low grade renewable heat sources, like shallow geothermal heat, or lift solar thermal energy to higher temperatures for residential or industrial uses as well. Heat pumps harnessing these heat sources require less electricity and enable the utilisation of non-electric, sustainable heat sources, which otherwise could be left unused.

According to the experts, the challenges in heat pump technologies are safe and efficient operation with improved and environmentally benign working fluids, higher efficiency at higher working temperatures on the warm side and lower at the cold side, smart operation in combination with other clean technologies, intelligent control as well as the ease of installation and a sustainable and affordable value chain. Development challenges for sorption heat pumps are improved active materials, component development and reduced system complexity and costs.

Cogeneration of (Cooling), Heat and Power

Large power plants use the technology of cogeneration of heat and power, mostly with steam and gas turbines. On a smaller scale, distributed cogeneration of heat and power is provided by micro-gas turbines, by Stirling engines or by fuel-cell technologies. Cogeneration is ideal for application in those places that have both electricity and heating/cooling demands and are increasingly important in flexible sector coupling. They also provide energy efficiency when coupled with district heating systems. Currently, most CHP plants depend on fossil fuels, particularly natural gas, because of its efficiency and widespread availability. As such, these systems should be viewed as transitional technologies on the path to renewable energy solutions. Shifting to renewable fuels is vital for reducing greenhouse gas emissions. Fuels like biogas, biomass, and hydrogen present increasingly feasible alternatives for CHP systems, helping to decarbonize energy production.

Thermal energy storage

The storage of thermal energy is used whenever there is a time delay between the highest production, and thus, availability of heat or cold, and its greatest demand for building users. This is of special interest for variable renewable sources, like solar thermal, but also for constant renewable sources with a varying heat demand, like geothermal. But thermal energy storage also can serve to manage energy systems, for instance to supply heat at peak demand times, increasing the overall energy system efficiency. The main types of TES include sensible, latent (phase change materials), thermochemical, and chemical storage. Sensible storage involves storing heat in a medium, often water, which increases its temperature. The higher the specific heat capacity of the medium, the more heat it can store. Water-based sensible storages are commonly found in household hot water boilers and heating buffers, as well as large-scale district heating and cooling networks. In some countries large Pit Thermal Energy Storages (PTESs), with a large reservoir of water to store energy, already provide seasonal storage, saving excess energy in the summer for the winter.

With phase change materials, PCMs, the heat is stored in the change of physical phase of the storage material, for instance from solid to liquid or from liquid to vapour. Commonly used PCMs are paraffins, fatty acids or salt hydrates. Less common and less technologically mature PCMs are based on solid-solid transitions and may offer interesting perspectives (e.g. intrinsic shape stability and superior thermophysical properties, but still need substantial research effort to become a viable solution. The advantage of PCM is that a high amount of heat can be stored at the phase change temperature. Therefore, this storage technology has great advantages in applications in which the temperature is ideally kept stable, like with indoor temperature control or with heat pump applications. PCM market products for buildings are building materials, or elements with intrinsic properties allowing them to absorb and release heat during phase transition cycles to buffer room temperature, while more and more hot tap water boilers with PCM enter the market.

In thermochemical materials, TCMs, heat is stored by causing a chemical change of the material. This can be in the form of sorption, where a vapour of one material is absorbed by a porous carrier material, like silica gel or zeolites. Or when a vapour is taken up by a salt, changing the crystal structure of the salt. This is seen with salt hydrates, taking up water vapour, or with ammoniates. With chemical storage, the uptake of heat leads to the formation of another chemical substance, like a metal hydroxide to a metal hydride. It generally takes higher temperatures to induce this kind of reaction. Both TCMs and thermochemical storage technologies are in a development phase and are expected to enter the market in the next five years.

Technology combination and integration

The range of applications of thermal components in buildings is large, from small individual dwellings and flats and larger multifamily dwellings to non-residential buildings with diverse heating and cooling demand patterns.

Heating & Cooling Systems are considered as a holistic technical system when designed. However, not all the systems are comprised by the same elements, nor with the same complexity. The materials used, the design and layout, the types of elements, their compatibility and performance, and the boundary conditions influence the behaviour of the system. Their combination/integration within a building, district or grid also requires the control to consider climate conditions, user behaviour, and building design/construction. This requires not only to know how any of the main elements works, but also how the whole system performs, including all the potential load losses in subsystems like generation, exchange circuits, transport, distribution, storage, and control. Combination refers to the joint design and use of subsystems for different thermal services, energy resources, residual heat, and electricity production and consumption. Integration allows diverse subsystems or systems to work together, improving efficiency, maintenance, space utilization, power system resilience (e.g., reduced peak demand, lower residual load), and heat recovery. As an example, integration of energy systems with water purification/treatment could provide further ways to optimally exploit energy peaks and improve economic sustainability.

District Heating and Cooling (DHC)

Buildings are connected to the electricity grid and partly also to heating or cooling grids. Traditionally, buildings were consuming elements in the grids, but increasingly, buildings are also used as generating or storage elements in grids.

DHC networks, also known as district energy systems or district energy networks, are centralised systems that produce and distribute thermal energy (heat or cold) to residential, commercial, and industrial buildings, through a network of insulated pipes, within a specific geographic area, such as a city or neighbourhood. A DHC network is composed of one or several plants that generate thermal energy using a variety of heat/cold sources or technologies and then distribute it to connected customers for space heating, hot water, or cooling, depending on the season and the needs. These networks are an efficient and sustainable way of meeting the heating and cooling needs of buildings compared to individual, decentralised heating, and cooling systems. They enable tapping into sustainable heat resources that would otherwise not be possible to exploit at a large scale. Hence, they foster more renewable, circular, and energy-efficient energy systems.

District heating and cooling is part of the ready-to-deploy solutions to phase out fossil fuels in heating and cooling. It currently represents 13% of the heat market, providing heat to more than 77 million European citizens, while 140 million citizens live in cities already equipped with a DHC network. In 2022 a total share of 42.6% of the fuel mix was covered by renewables and waste heat sources[4]. DHC fosters a robust decarbonisation pathway for the heating and cooling sector by using local renewable heat such as sustainable bioenergy, geothermal and solar thermal energy and enabling the use of waste heat from industrial and tertiary sources. This use of multiple sources results in a more stable and price-hike resilient system. DHC networks could also play an essential role in balancing the electricity grid while integrating a significant amount of renewable electricity, which is a new, innovative way of sector coupling.

This comes with several challenges for the future developments and implementation. More must be known about the profile and dynamics of the generating and storage possibilities of buildings, while protocols are needed to enable a proper interaction between grids and buildings connected. Measures for better integration of renewable energy systems as well as higher temperature levels for cooling to reach higher efficiency should be implemented in the DHC of the near future. Forecasting methods and market structures are required to find an

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[4] https://prod.euroheat.org/data-insights/outlooks/dhc-market-outlook-2024

optimised balance and functioning of the grids for a given time-ahead period. Finally, optimization of the building heating system is needed to reduce the temperature level of the heating network for lower supply and return temperatures.

Scope

This White Paper includes all clean heating and cooling technologies and thermal energy storage technologies that are applied in the built environment. This can be on the scale of single or multifamily houses, detached or terraced, on the scale of apartment buildings, tertiary buildings like hospitals, schools, sport facilities and shopping malls, and office buildings. It also includes those clean technologies that are coupled to district heating and cooling systems.

3. Implementation

How can the clean heating and cooling and thermal energy storage technologies be implemented? After the introduction of the technologies in the previous chapter, you will now see what the main gaps and barriers are for each technology, and with which activities the targets for these can be achieved. First, the main targets, that also have been adopted in the Implementation Plan of the IWG5, are listed. Then, the gaps, barriers, targets and activities for each technology will be described in more detail. More extensive descriptions of the challenges and the proposed actions and expected outcomes are described in the activity fiches, that are appendices of the Implementation Plan of the IWG5[5].

Main Targets for Clean Heating and Cooling and Thermal Energy Storage Technologies

Target 5.2-T1 Heat Pump Systems:

- Development of prefabricated, fully integrated plug-and-play hybrid/multisource heat pump systems and integrated compact heating/cooling plants based on a modular heat pump
- Full-scale demonstration of heat upgrade technologies for district heating networks with supply temperatures in the range 90 - 160°C
- Increase the number of heat pumps across Europe to 10 million by 2027

Target 5.2-T2 District heating and cooling:

- Increase the share of district heating in the EU's heat demand to 20% by 2030, preferably using low temperature waste heat and renewable sources
- Integration of 8 million households into the district heating/cooling networks across Europe

Target 5.2-T3 Micro CHP/CCHP:

- Integration of highly flexible CCHP systems with heat storage, heat pumps and renewable heat sources with the aim of reducing annual fuel consumption
- Development of CCHP technologies running on renewable gases (hydrogen, ammonia, methanol, synthetic gas, etc.) with comparable performances as running on natural gas
- Development of CCHP solutions with post-combustion treatments to reduce emissions by >50% and keeping operational flexibility

Target 5.2-T4 Thermal Energy Storage:

- 100 new large thermal energy storages in district heating and cooling networks in progress in 2030
- 10 new demo systems with sensible thermal energy storage with a usage of RES and waste heat to more than 60% of the yearly heat demand
- 20 systems for compact thermal energy storage demonstrated at TRL 6/7 with a storage density at system level increased to 120 kWh/m^3

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[5] https://www.iwg5-buildings.eu/resources/reports/

Target 5.2-T5 Solar Thermal Systems and PVT:

- Cost reduction for solar thermal combi-systems with high solar fraction (min. 60%), towards a range of 12-16 €ct/kWh
- Development of standardised solutions for easier integration of solar thermal in building renovation, in particular in active prefabricated building elements
- Cost reduction of PVT panels by a factor of 1.5 to 2 from the 2020 reference value of €1000/m², also by ensuring easier installation

Heat pumps

Gaps and Barriers

During the discussions about the gaps and barriers of heat pump technologies, a division into 3 subcategories was defined: compression, thermally driven and lower TRL heat pump technologies like thermoacoustic, thermoelectric, and magnetocaloric. The following contents apply to all technologies unless explicitly stated.

The **safe and efficient operation** with e.g. low GWP refrigerants for compression heat pumps was identified as a challenge to implement these new materials in a safe, efficient, and practical way. Additionally **high efficiency at higher heating system temperatures** was discussed to be able to replace fossil fuel boilers in some buildings. **Smart operation** in combination with other technologies like photovoltaics or batteries as well as **self-optimising control** by using sensor data for predictive models are further challenges. Finally, the **ease of installation** by providing tools and guidelines for installers as well as digital systems for self-commissioning and a **sustainable and affordable value chain** by e.g. modularization and integration of components in a heat pump was included in the list as a gap or barrier.

Measurable targets (Target 5.2-T1 Heat Pump Systems)

The following targets were proposed for the implementation plan:

- Development of prefabricated, fully integrated plug-and-play hybrid/multisource heat pump systems and integrated compact heating/cooling plants based on a modular heat pump
- Full-scale demonstration of heat upgrade technologies for district heating networks with supply temperatures in the range 90 - 160°C
- Increase the number of heat pumps across Europe to 10 million by 2027

Activities

Research in **safe and efficient operation** with low GWP refrigerants (2025-2030). The extent to which hydrocarbon refrigerants can be used in split systems or indoor applications with manageable risks should be investigated. This includes design of safety systems, including sensors etc, but also miniaturization of components to contain small refrigerant charges.

High temperatures (2025 onwards) for retrofitting heat pumps to share existing properties to a considerable extent. Increased R&I efforts are needed to ensure efficient and robust operation even at higher temperatures than today. This also applies to the design and optimization of large heat pump systems that can work efficiently and flexibly in district heating systems.

Heat pumps with **smart operation** (2025-2030) should predict in advance what their energy requirements are, based on house type, user demand and weather forecast. The heat pump should be able to calculate how to best fulfil the heating demand of the building, based on different optimizing. Algorithms learning the properties of buildings and installations, and the users, should be researched to accelerate this process.

Research must be done in developing tools and methods to **simplify the installation** (2025 - 2027) for installing parties to select the appropriate equipment, to keep installations as simple as viable, to configure the system correctly and to identify faults and which measures to take.

District Heating and Cooling

Gaps and Barriers

During the online discussion with the experts, the topic of a **better integration of renewable energy systems** as well as **higher temperature levels for cooling** to reach higher efficiency were identified as key challenges. Additionally, the **optimization of the building heating systems** was recognized, to minimize the temperature levels in district heating networks. This would reduce losses and increase the efficiency of the operation and control of the indoor heating system elements, allowing the system to run on lower supply and return temperatures.

A further task are the needed **profiles and dynamics** of the generating and storage possibilities of the building, while **protocols** are needed to enable a **proper interaction between grids and buildings**. **Forecasting methods** and **market structures** are required to find an optimised balance and functioning of the grids for a given time-ahead period. In some EU member states the price of electricity, partially because of the energy taxes, is also a barrier for the DHC networks to better integrate electricity.

Measurable targets (Target 5.2-T2 District heating and cooling)

Following targets were proposed for the implementation plan:

- Increase the share of district heating in the EU's heat demand to 20% by 2030, preferably using low temperature waste heat and renewable sources
- Integration of 8 million households into the district heating/cooling networks across Europe

Activities

The activities are being developed in the research and innovation field and the uptake of green energy and waste heat for providing useful heat. In the short-term perspective (until 2030) there are a series of currently running projects focusing on investigating novel ways of **harnessing waste heat,** like from data centres, and the use of **renewable energy**, including low-grade heat. There are projects aimed at **developing skills and increasing the qualifications of professionals** working in the heating sector, and other aimed at integrating **new heat storage technologies**.

Another key action for 2030 is **increasing the district heating/cooling systems' flexibility**, **digitalisation, and efficiency increase** through heating water temperature reduction. For the short-term impact, **renewables and waste heat sources** are expected to account for **50% of the energy** used to provide heat **for district heating systems**.

By **adopting and further enhancing the policies** developed before regarding R&D&I and breakthrough technologies, it is expected that the district heating systems are developed in new areas where it is required and further ameliorated where it is already in place. The aim is to **reach 48% market share for DHC in Europe's heating sector in 2050.**

Micro CHP and CCHP

Gaps and Barriers

Present micro-(C)CHP technologies mostly are driven by fossil fuels. Innovative solutions **powered by green fuels** (or e-fuels) will play an important role in providing distributed heat, cold and electricity. By generating both heat and power on-site and utilizing clean energy sources in form of green fuels, these systems can contribute to **alleviate electricity grid congestion** and provide a reliable and dispatchable energy supply. Additionally, they offer the flexibility to **adapt to different fuels** and evolving energy landscapes, making them a versatile solution for the decarbonized energy scenario. While microgasturbines themselves are not a new technology, their application in building heating and cooling systems fed by green fuels represents a novel and potentially transformative approach.

Measurable targets (Target 5.2-T3 Micro CHP/CCHP)

Following targets were proposed for the implementation plan:

- Integration of highly flexible CCHP systems with heat storage, heat pumps and renewable heat sources with the aim of reducing annual fuel consumption
- Development of CCHP technologies running on renewable gases (hydrogen, ammonia, methanol, synthetic gas, etc.) with comparable performances as running on natural gas
- Development of CCHP solutions with post combustion treatments to reduce emissions by >50% and keeping operational flexibility

Activities

Two main activities can be defined for the development of innovative micro-CCHP technologies:

1: Broad spectrum development and experimentation for hydrogen combustion system (from TRL6 to TRL7, time frame 2025 - 2028)

Develop high flexible **dual fuel** (hydrogen/natural gas) combustion systems for microturbines to burn any concentration of mixtures of hydrogen in natural gas from 0% hydrogen (100% natural gas) to 100% hydrogen. Review state of the art, simulation and modelling, hydrogen / natural gas combustion chamber and fuel system design, combustion system prototype detailed design and procurement, combustion system prototype testing, data processing and emissions evaluation, enhanced design.

2: High flexibility development and experimentation for **methanol and hydrogen combustion** systems (from TRL6 to TRL7, time frame 2025 - 2028)

Starting from state-of-the-art combustion systems, define **flexible operating concepts** (for different use context) able to cope with high variability of trigeneration demand, minimizing emissions. Testing transient operations, minimum load and part loads, assess capabilities and emissions in a wide spectrum of cases.

Thermal Energy Storage

Gaps and Barriers

Sensible thermal energy storage is the most developed and applied presently in the built environment, in various domestic-scale and DH-scale forms. Higher temperature sensible storages are being developed for power-to-heat purposes, both in small and in large thermal systems. They will play an important role in flexible sector coupling, with smaller systems also relevant for the built environment.

Challenges are the **cost reduction** of sensible TES, the exploration and demonstration of **new business models** for sector coupling and the **system integration**.

Phase change materials (PCMs) are the compact TES type that also has a high technology readiness level (TRL) today, with many market-ready systems with ice and some with other materials. Despite these successes, PCM design has many techno-economic challenges to overcome, at material, component and system level, to realize their widespread and particularly large-scale deployment.

Thermochemical storage materials (TCM) have the potential for the highest compactness and are still in a lower TRL, with a few startup companies working on market introduction of specific TCM technologies. The challenges are at different levels: material, component and system.

For PCM storage and TCM storage, the challenges broadly are:

Improved materials, with better supercooling, lower hysteresis, no phase separation, high thermal conductivity, satisfactory thermal and chemical stability for repeated cycling, finding renewable **cost-effective alternative solutions** etc. Furthermore, costs can be reduced by improvement of material **production methods** and by using recyclable, sustainable and low-cost reagents.

Increased component performance, with effective heat exchangers or reactors, including incorporation of heat recovery systems, for satisfactory charging/discharging powers without significant compromises on effective TES size and costs, as well as application-scale long-term cycling testing of materials in the components.

Optimised systems, with smart operation and control, in combination with building energy systems and for flexible sector coupling services. Furthermore, enhancing the system energy storage density is important to reduce system cost. This can be achieved by new concepts e.g. with a dynamic PCMs mode for latent TES.

A **general challenge** for all TES technologies is to find good business cases for the storage options. A financial justification should be found for any TES on the market, peak shaving, load shifting, energy efficiency improvements, increased use of renewable sources, increased waste heat recovery and flexible sector coupling services.

Measurable targets (Target 5.2-T4 Thermal Energy Storage)

Following targets were proposed for the implementation plan:

- 100 new large thermal energy storages in district heating and cooling networks in progress in 2030
- 10 new demo systems with sensible thermal energy storage with a usage of RES and waste heat to more than 60% of the yearly heat demand
- 20 systems for compact thermal energy storage demonstrated at TRL 6/7 with a storage density at system level increased to 120 kWh/m3

Activities

General: Studies into the **business cases** for TES technologies

Sensible TES: Further **cost reduction** through technology improvements, through manufacturing/building process improvements, through build-up of practical experience with demonstration and monitoring projects and through standardisation.

PCM TES: **material and encapsulation design** and optimization with e.g. additives and fillers, pilot, **heat exchanger design, compact system design,** pilot- and application-scale numerical and experimental **system studies**, monitoring of real installations for **long-term performance** & comparison for design versus real performance, **standardization of interfaces** / ports for the connection between TES and energy system.

TCM TES: Development, refinement and design of **novel materials,** integration and testing within complete storage systems to validate these advancements (TRL 3-5), establishing an **open platform** incorporating data from previous projects to facilitate collaboration and accelerate progress in the field, setting up **networks of experts** for effective collaboration, through initiatives like COST actions (TRL 1-3), establishment of **training programs** across diverse disciplines of material science and engineering (TRL 1-3), **demonstration** of TES technology for weekly, monthly and seasonal storage (TRL 5-7).

Solar Thermal and PVT

Gaps and Barriers

One of the well-known **limitations of solar technologies** is that their energy output on solar radiation, which varies based on geographical location, season and weather conditions. This dependence leads to the need for auxiliary equipment to **increase the solar share and thus provide more flexibility** such as thermal energy storage (TES).

Another constraint is space availability, although solar thermal technologies have the highest energy density among all solar technologies, having an efficiency of around 70%. This constraint can be more relevant for large-scale installations such as solar district heating, since these must be located relatively close to the end-users.

Similarly to most renewable energy solutions, the **upfront investment** for these technologies, especially at large scale, is higher than for fossil-based solutions. For **PVT systems, a cost reduction** is still needed for the technology too.

Lastly, solar thermal cooling still need research, innovation and testing to reach higher TRLs and become widely available on the market.

Measurable targets (Target 5.2-T5 Solar Thermal and PVT)

The following targets were proposed for the implementation plan:

- Cost reduction for solar thermal combi-systems with high solar fraction (min. 60%), towards a range of 12-16 €ct/kWh
- Development of standardised solutions for easier integration of solar thermal in building renovation, in particular in active prefabricated building elements
- Cost reduction of PVT panels by a factor of 1.5 to 2 from the 2020 reference value of €1000/m², also by ensuring easier installation.

Activities

One of the main challenges when dealing with solar systems consists of **cost reduction** and to ease the deployment by **pre-fabrication** and **plug-and-play** equipment. The **industrialization** of these systems also allows the scalability of the solar power plants.
And finally, R&D&I still have room for **improvement** for these solar technologies, such as solar concentrators for building use, solar façade systems, or other **innovative designs** and applications either individually, or as part of combined systems with other technologies.

Three main activities are considered regarding solar thermal and PVT:

- **Activity 1: Large-scale solar thermal and PVT applications (TRL 6-8)**
- **Activity 2: Prefabricated and modularized solar thermal and PVT systems for single family houses (TRL 6-8)**
- **Activity 3: Medium-sized solar thermal systems for multi-dwelling and service buildings.**

Technology combination and integration

Gaps and barriers

Technology combination deals with the sum of the subsystems, and with the challenge of **putting all of them together** in harmony. It includes energy generation, heat production and exchange, energy distribution, potential balancing the power grid, and storage, among others. Integration implies having a perfect fit within the infrastructure to provide energy, in this case buildings, which results in other adjustments and **risks**, as technical, constructive, and operational, to be solved in **earlier stages of design**, when possible, to avoid overlaps, misfunctioning, or other problems in the building use stage.

To **prevent risks** of failure or unexpected events, more sophisticated control systems are required, which needs a more accurate and costly initial investment surveillance, and maintenance. The **commissioning and fault detection** become more critical, needing data collection, machine learning/AI support to accelerate the analysis and early detection.

The diversity of energy **consumption patterns** by building users' needs to be considered in early system design, to optimize operation, balancing and energy management.

Another barrier when considering large and complex systems is linked to **inefficient distribution** networks, which may lead to heat or power losses.

The **lack of** normalized, transparent and complete **libraries** when modelling, results in uneven, conflicting and incompatible outcomes, hampering the aim of the energy transition.

Regarding the complexity of these systems, assessing the performance under real conditions is necessary, and some additional knowledge on the overall energy system could be required, led by a qualified team of **skilled workers** and building operation and maintenance staff, besides clear instructions in a safekept document, to be potentially consulted in any time of the building use, maintenance and renovation stages.

Measurable targets

Due to the connection of this activity with almost all other technologies in this white paper, Targets of 5.1-T1, T3, T4 and T5 are all addressed. See above for a listing of these targets.

Activities

Define potential subsystems to be combined/integrated, and of the **assessment parameters** to determine for each of them. Implement smart and enhanced **system design**, using Digital Twins, BIM or other Digital Building/Grid Modelling, with manufacturers/ providers facilitating combination/integration **guidelines and tolerances**. Implement of **Life Cycle Assessment stages**, from cradle to end-of-life. Develop, compare, and update industry standards, testing protocols, and certification processes, to harmonize assessments and boundary and testing conditions and thus, warranting a legal framework. Evolve **guidelines** to provide safety, energy efficiency, and sustainability for combined/integrated heating & cooling systems. Generate **Cost-Benefit Analysis** according to different scenarios, and system compositions. Create **open data bases** for different elements, technologies and auxiliary components, to be modelled and assessed through digital tools. Develop **algorithms for auto-adapting** heat/cooling installations.

4. Conclusion

It is a grand challenge to make sure that the built environment will be using only renewable energy and waste heat sources before 2050. The diversity of building types, building use and location make it impossible to find a universal solution. This White Paper gives direction to the possible solutions to the challenge, by addressing the clean technologies that are in place to reap, store, convert and use sustainable sources in buildings.

For heat pumps, that already supply a considerable part of the buildings with heating and cooling, work is to be done in guaranteeing a safe and efficient operation, in novel technologies to supply heat at higher temperatures, in smart control systems and in the further simplification of the installation process.

District heating and cooling has clear advantages in densely populated areas and has large growth opportunities. Developments are needed in increased flexibility, increase the share of renewable energy sources that feed into the systems, in developing skills and qualifications of the work force, in increased flexibility and digitalisation and in enhanced policies supporting the expansion of district heating and cooling systems.

Micro cogeneration of cold, heat and power can provide the three energy forms in an effective, distributed way. The technologies must be adapted to the switch from fossil fuels to renewable fuels. Flexible, dual fuel technologies for either gaseous of liquid fuels are needed, and the operational concepts should be flexible, playing an increasingly important role in distributed, flexible sector coupling.

Thermal energy storage technologies offer flexibility and an increased use of intermittent renewable energy sources, from the single household scale to the district heating grid scale. In general, with the transforming energy landscape, novel business cases for thermal energy storage are needed. Technology development needs are broad, resulting from the large variety of thermal energy storage technologies: storage material improvement from a basic science to applied level, component development, system integration, interface standardisation, experts network development, training programs and further demonstration to accelerate the uptake of novel technologies and applications.

Solar thermal and PVT technologies are increasingly applied to provide heat and electricity on a local but also district scale. Work is needed to further reduce the cost by pre-fabrication and plug-and-play solutions, and to find standardised solutions for easier integration, especially in building renovation.

A significant challenge arises from the variety of clean heating and cooling technologies used in buildings. The integration and combination of these technologies pose development challenges in the areas of defining appropriate sets of assessment parameters, in smart system design using building information models, in the implementation of life cycle assessment techniques, in realising guidelines for safety, energy efficiency and sustainability, in practical cost-benefit analysis methods and in the creation and use of open databases enabling the further use of digital tools from design to operation and maintenance.

These areas are not isolated, and attention is also needed for other areas that are coupled to clean energy technologies and thermal energy storage in the built environment: measures to decrease the energy consumption of buildings through novel building materials and better design and construction of buildings; the coupling with other elements of the energy systems like industry and mobility; social acceptance and legal aspects and of course financial aspects. These external areas are partly covered by other white papers of the Implementation Working Group 5 and partly by the activities of other SET Plan elements.