European Commission

Coupling of Heating/Cooling and Electricity Sectors in a Renewable Energy-Driven Europe

ETIP SNET

European Technology and Innovation Platform Smart Networks for Energy Transition

RHC Renewable Heating & Cooling

European Technology and Innovation Platform

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LIST OF ABBREVIATIONS

AC	Alternate current
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
BtL	Biomass-to-Liquid
CAES	Compressed Air Energy Storage
CCFD	Carbon Contract for Difference
CCP	Combined Cooling and Power
CHP	Combined Heat Power
CSP	Concentrated Solar Power
CST	Concentrated Solar Thermal
DC	Direct current
DHC	District Heating and Cooling
ERDF	European Regional Development Fund
ESI	Energy Systems Integration
ETC	Evacuated turbo collectors
ETES	Electrothermal Energy Storage
ETS	Emissions Trading System
FB	Fluidised Bed
FPC	Flat plate collectors
GHG	Greenhouse Gases
GtH	Gas-to-Heat
H/C	Heating/Cooling
IoT	Internet of Things
LAES	Liquid Air Energy Storage
LCoE	Levelised Cost of Energy
LFC	Linear Fresnel collectors
LPG	Liquid petrol gas
OEM	Original Equipment Manufacturer
ORC	Organic Rankine Cycle
PBtL	Power-and-Biogas-to-Liquid
PCM	Phase Change Material
PEMFC	Proton-Exchange Membrane Fuel Cell
PtH, P2H	Power-to-Heat
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtT	Power-to-Thermal
PTC	Parabolic trough collectors
PV	Photovoltaics
PVT	Photovoltaics Thermal Collectors
PTES	Pit Thermal Energy Storage
RES	Renewable Energy Source
RHC	Renewable Heat and Cooling
sCO_2	Supercritical CO_2
SDH	Solar district heating
SHIP	Solar Heat for Industrial Processes
SOFC	Solix Oxide Fuel Cell
TCM	Thermo-mechanical Material
TFC	Trilateral Flash Cycle
TRL	Technology Readiness Level
TTES	Tank Thermal Energy Storage
UTES	Underground Thermal Energy Storage

EXECUTIVE SUMMARY

The White Paper "Coupling of Heating/Cooling and Electricity Sectors in a Renewable Energy-Driven Europe" focuses on the implications of coupling the electricity, heating and cooling vectors as a vital part of efficiently decarbonising the whole European energy sector. To achieve decarbonisation, different renewable energy technologies for electricity and heating and cooling are needed, and in many cases, they could be coupled to increase energy efficiency. In addition to the traditional connection of heat and electricity in combined heat power (CHP) and Cogeneration plants, this White Paper elaborates on promising, often decentralised generation side as well as demand side technologies and solutions aimed at achieving efficient decarbonisation in terms of both energy efficiency and infrastructure optimisation.

The "Fit-for-55" package is the first important milestone to reach carbon neutrality by 2050. It sets out concrete measures to reduce net greenhouse gas emissions by at least 55% by 2030, increase energy efficiency by 13% and lift the uptake of renewable energy to 45%. Many efforts are still needed to decarbonise the heating and cooling sector, it is lacking behind the electricity sector (2020: 23,1% vs. 37,5%, source Eurostat) A decarbonisation of the heat sector is important to reach the decarbonisation targets for the energy sector. In particular, the heat sector represents the most considerable portion of the European energy demand: half of the final energy consumption and a larger share of carbon emissions. Demand for heat comes from the residential, industrial and service sectors. Therefore, heating and cooling have to contribute heavily and fast to the reduction of greenhouse gas emissions. This can be achieved by increasing the share of renewable sources for heat and cold generation and through direct and indirect electrification (sector coupling solutions). In order to build up a reliable, sustainable and cost-effective energy supply system in Europe, flexible generation of electricity, heat and cold, and any kind of energy storage are needed to ensure the security of supply and decarbonisation. Both the successful implementation of sector coupling (cross-vector sector coupling and the end-use sector coupling) and a fully integrated energy system in a holistic power system architecture comprising all interactions within the power system itself, between the network - generation - and storage operators, consumers and prosumers, through market mechanisms, are mandatory for a successful energy transition and decarbonised supply of heat and cold.

This White Paper provides an overview of the different sector coupling technologies: Renewable energy conversion technologies (solar-based combined generation, direct conversion of solar energy into heat, geothermal-based generation, biomass technologies, and hydrogen-based technologies), Renewable heat and heat recovery technologies (direct conversion of renewable electricity into heat, heat pump technologies, solar thermal technologies, innovative waste heat recovery cycles), Polygeneration (Cogeneration, Trigeneration) and District heating.

This White Paper also describes the important role of the different storage technologies (e.g. thermal energy storage, chemical storage, i.e. hydrogen or synthetic fuels as the basis for decarbonised CHP and Cogeneration application) as sector coupling components to store excess renewable energy and thus to contribute to a sustainable and reliable energy system. Due to the focus on heat/cold applications, other forms of storage within the power grid (e.g., direct electrochemical storage, hydro pumps, electrical/magnetic storage) are not considered in this document. It is, in any case, well understood that batteries deliver significant contributions to storing excess renewable energy, especially in the context of sector coupling with the mobility system, ancillary services and home electricity storage solutions.

The existing electrification and heating/cooling technologies are the basis for a fully decarbonised energy system. Their maturity status is briefly outlined in Chapter 4 whose message is that some of the existing technologies need to be scaled up to become economical. Chapter 5 highlights the importance of storage as a key element for coupling in all sectors. However, certain measures and efforts on R&D and market stimulation are needed to improve the technologies and to allow full system integration, thereby capturing the benefits of sector coupling. Chapters 6 and 7 describe the R&D needs and challenges to further develop the components and solutions necessary to deal with the increasing share of renewable energies in the grid, e.g. for sector coupling components, heat and power demand management systems, storage from energy system integration viewpoint and innovative business models.

Public funding from European instruments is necessary to accelerate the development of the related technologies/systems, reduce the burden from technical and business risks, and support market uptake. From plant operators' perspective, CAPEX and/or OPEX funding from European funding instruments is necessary to reduce the financial risks and to contribute to establishing positive business cases.

As the transition towards a green future must be accelerated, new concepts should be already available and verified, at least at the prototype level. Available technologies need to be quickly up-scaled from pilot to real plant sizes, and investments have to be stimulated by regulations and incentives based on, e.g., CO_2-pricing worldwide emission trading systems.

To make clean and integrated technologies the standard, the market framework and the political mindset must change to make these technologies economically more competitive. Furthermore, renewables-based solutions should benefit from streamlined permitting and be given financial and institutional incentives while removing administrative burdens. The potential for intensified use of District Heating and Cooling (DHC) systems is meaningful across the EU.

The energy transition towards renewable heating and cooling requires both technical, legal and economic skills. While the economic and legal framework is currently being shaped, a lack of design, planning and installation skills emerges. Quite often, the different sectors compete for the same competencies. Hence a thorough assessment and EU-wide coordination effort are recommended to ensure the education and training of a sufficient number of designers, planners and installers by making the "renewable energy" career path attractive and providing enough education and (re-)training facilities.

1. INTRODUCTION: CURRENT SITUATION AND WAY FORWARD

To mitigate impacts of climate change, all economies around the world urgently need to decarbonise their energy systems. Europe has a key role in the global energy transition towards low-carbon energy systems. Therefore, Europe needs to support its industries and research institutions to innovate accordingly, thus maintaining and enhancing competitiveness at all levels. A backbone of Europe's energy system is on the one hand the shift towards renewable energies and on the other hand the electrification of several sectors. Especially in the heating and cooling sector, the role of electrification is expected to steadily increase. At the same time the use of biomass is currently the largest renewable energy source for heating and cooling and will also continue to develop[1]. The central future role of electricity in the European energy system is presented in Figure 1. Increasing electrification of the transport and heating and cooling sectors poses challenges to the electricity grid, which can be solved with smart sector coupling solutions. Energy systems stability and supply security require more reliance on available local thermal renewable energy sources and coupled thermal, electricity and chemical storage.

While using all available local renewable energy sources and associated infrastructures for all applications, the massive energy transformation of the European economy (residential, tertiary, industry, agriculture, and transport sectors) will require full digitalisation and flexible electricity interconnections[2].

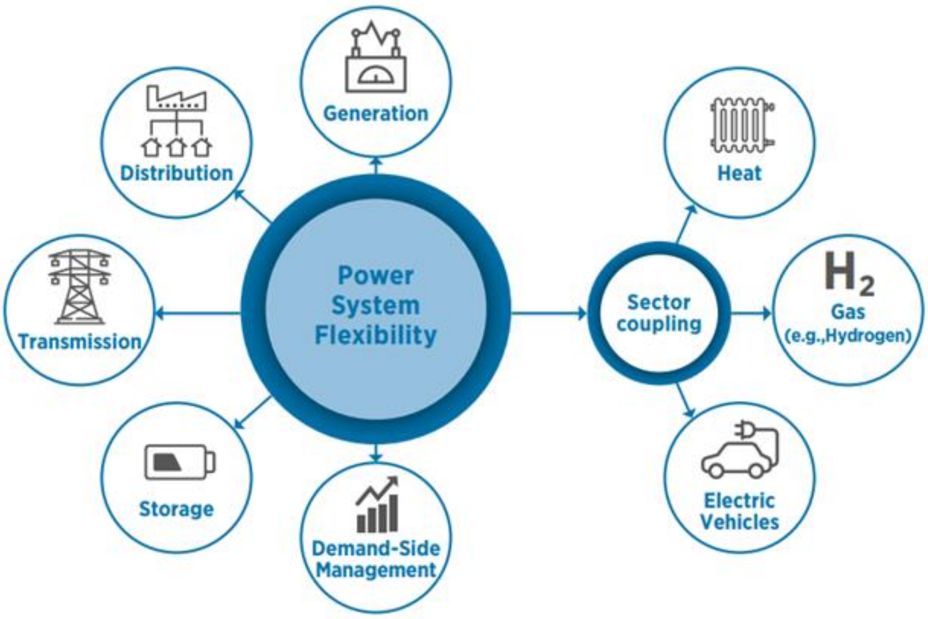

Figure 1: Decarbonisation of all sectors means massive electrification[3]

[1] ETIP SNET Vision 2050, published 2018
[2] IEA (2017), Digitalisation and Energy, IEA, Paris https://www.iea.org/reports/digitalisation-and-energy
[3] IRENA (2018), Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers.

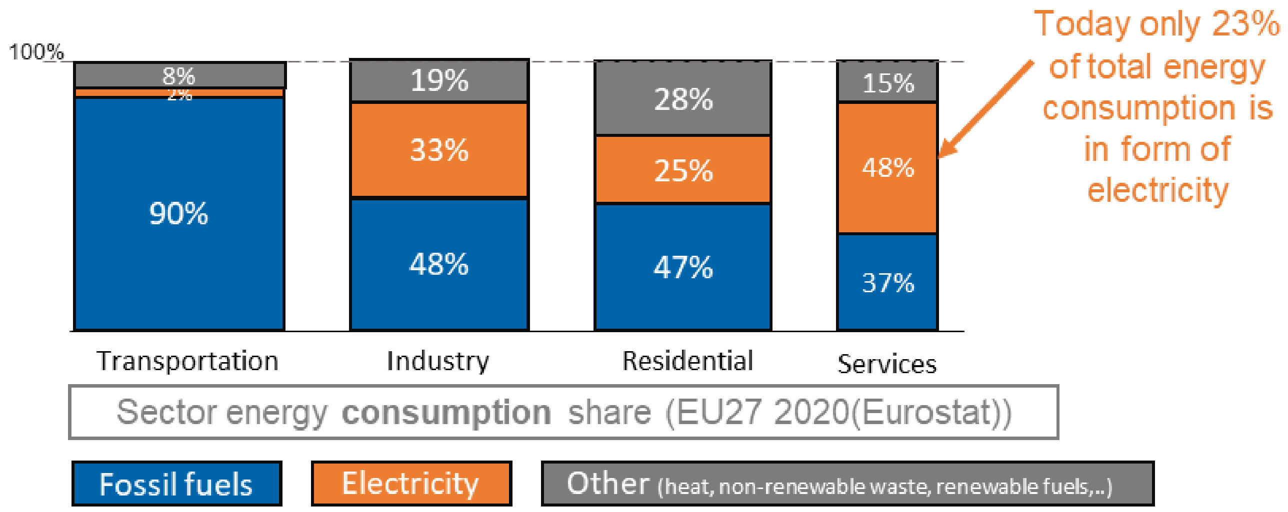

Figure 2: Share of renewables in different sectors[4]

The heating and cooling sector plays an essential role to successfully address the climate change challenge and to achieve decarbonisation of the energy system. Each year, almost 50% of the final energy consumed in Europe is used for heating, cooling, or refrigeration for residential, tertiary, or industrial purposes. The vast majority (around 75%) of this energy demand is provided by the combustion of fossil fuels causing considerable environmental damage, including in terms of greenhouse gas emissions and air pollution – while only 19% is generated from renewable energy. Today, the social, environmental, and economic costs of climate change make the mission of quickly embracing more sustainable sources of energy urgent. Recognising this situation, the European Technology and Innovation Platform on Renewable Heating and Cooling (RHC ETIP), aims at playing a decisive role in protecting Europe's leading position in renewable heating and cooling technology.

The RHC-ETIP takes a holistic view of research and innovation priorities related to renewable heating and cooling technologies, providing strategic insight into market opportunities and needs[5]. It has been instrumental in raising the profile of the renewable heating and cooling sectors through its recommendations for research priorities and project ideas. Together with the ETIP SNET, ETIP RHC outlines the necessity and benefits of closer coupling the electricity and heating/cooling sectors to accelerate the decarbonisation efforts in Europe[6].

The main drivers to achieve this objective are a higher rise of renewable energy sources (for electricity and heating), up to 45% of final energy consumption in 2030, as per REpowerEU communication, and the increase in energy efficiency in industry, buildings, tertiary, and transport.

On the one hand, in order to achieve complete decarbonisation, all sectors as transportation, industry, residential and services need further electrification. On the other hand, power generation must be completely decarbonised.

[4] EUROSTAT, 2018
[5] ETIP RHC Vision 2050, position paper
[6] "Strategic Research and Innovation Agenda for Climate-Neutral Heating in Europe" ETIP RHC Position paper, 2020

2. THE "FIT-FOR-55" PACKAGE AND "REPowerEU" PLAN TO ACCELERATE THE ENERGY TRANSITION IN ALL SECTORS[7]

The "Fit for 55" package contains comprehensive legal proposals for initiatives on EU's climate, energy, land use, transport, and taxation policies (directly linked to the European Green Deal) for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. This is a crucial point and a concrete roadmap to Europe becoming the world's first climate-neutral continent by 2050. The "Fit for 55" package is based on a whole-of-economy approach for a fair, competitive and green transition. This comprehensive and interconnected set of proposals include several aspects related to the activities of ETIP-SNET and ETIP-RHC. They have recently been further boosted by REPowerEU plan.

The package puts forward a series of legal proposals. Those will need to be adopted by the co-legislators and involve, specifically:

- The European Commission (EC) has proposed a reduction of the overall emissions and increased its annual rate of reduction on the EU Emissions Trading System (ETS).
- Member States should spend the entirety of their emission trading revenues on climate and energy-related projects.
- Review of Effort Sharing Regulation, which assigns strengthened emissions reduction targets to each Member State for buildings, road and domestic maritime transport, agriculture, waste, and small industries.
- Energy production and use accounts for 75% of EU emissions, so accelerating the transition to a greener energy system is crucial. According to the REPowerEU plan published on 18 May 2022, the Renewable Energy target of 5% will be increased to 45% of our energy from renewable sources by 2030. Sustainability criteria for the use of bioenergy are strengthened and Member States must design any support schemes for bioenergy in a way that respects the cascading principle of uses for woody biomass.
- Revised Renewable Energy Directive will require Member States to increase the use of renewable energy in heating and cooling by +1.1 percentage points each year, until 2030
- The Energy Efficiency Directive will set a more ambitious binding annual target for reducing energy use at EU level, in order to reduce overall energy use, cut emissions and tackle energy poverty, i.e. 13% energy saving compared to 2020 reference scenario.
- All new cars registered as of 2035 will be zero-emission, hence all the technologies and infrastructures necessities for zero-emission mobility must be developed. Notable efforts should be done on the substitution of aviation and maritime fuels.
- A revision of the Energy Taxation Directive proposes to align the taxation of energy products with EU energy and climate policies, promoting clean technologies and removing outdated exemptions and reduced rates that currently encourage the use of fossil fuels.
- A new Carbon Border Adjustment Mechanism will put a carbon price on imports of a targeted selection of products to ensure that ambitious climate action in Europe does not lead to 'carbon leakage'

[7] Europes-fit-for-55-package,https://ec.europa.eu/commission/presscorner/detail/en/IP_21_35412021;
REPowerEU: affordable, secure and sustainable energy for Europe (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en)

3. DEFINITION OF ENERGY SYSTEMS INTEGRATION, SECTOR COUPLING AND HOLISTIC ARCHITECTURE

The scope of this White Paper is the evaluation of existing technologies using renewable sources and identifying research and development needs to adapt them or develop new ones to enable the coupling of various sectors such as electricity and heating and cooling. Coupling with the gas sector is not in the scope of the paper. For better understanding, the clarification of various relevant terms are provided in the following.

Energy Systems Integration

Energy Systems Integration (ESI) coordinates the operation and planning of energy systems across multiple pathways and geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment[8]. It covers the entire economy divided into sectors to determine the proportion of a population involved in various activities[9]. Most economic models divide the economy into three sectors: Primary, which extracts or harvests products from the earth, raw materials and basic foods; Secondary, which produces finished goods from the raw materials extracted by the primary economy; and Tertiary, which is known as the service industry.

Sector coupling

ESI connects energy systems of various vectors within the second sector, i.e. Cross different Vectors of the energy utilities such as electricity, heating and cooling, and gas. The Cross-Vector Sector Coupling integrates these various energy infrastructures and vectors. In contrast, the End-Use Sector Coupling[10] involves integrating different infrastructures, such as electricity, heating and cooling, etc. within the customer plants. An efficient energy system optimises also the two aspects, i.e. the optimal allocation of available energy sources to the desired final uses, according to the respective characteristics (in time, in space, in production profile, etc.) in order to capture synergies and complementarities.

***LINK*-holistic power system architecture**

The *LINK*-holistic power system architecture is based on *LINK* Paradigm[11] ,derived from "Smart Grids" fractal pattern. It merges all relevant components of the power system into one single structure. These components comprise the electricity producers and storage regardless of technology or size, e.g., big power plants, rooftop PVs, etc., the grid regardless of voltage level, e.g., high-, medium- and low voltage grid, and the customer plants and electricity market, Figure 3. This holistic architecture unifies all interactions within the power system itself, between the network-, generation- and storage operators, consumers and prosumers, and the market, thus creating the possibility to harmonize them without compromising data privacy and cybersecurity. It facilitates all necessary processes for a reliable, economical, and environmentally friendly operation of smart power systems. It allows a clear description of the relationships between different actors. It creates conditions to go through the transition phase without causing problems. It enables Energy Communities, the Sector Coupling and couple with the non-energy sectors such as health and comfort. The main principle of the *LINK*-Solution is optimising the whole Smart Grids by coordinating and adapting the locally optimised Links. The same principle also applies to Sector Coupling, where the optimisation of the electricity system and other systems (in this document, heating and cooling systems) realises by coordinating and adapting the locally optimised systems.

[8] O'Malley M at al. (2016) Energy Systems Integration: Defining and Describing the Value Proposition. The International Institute for Energy Systems Integration, Technical Report NREL/TP-5D00-66616. doi: http://dx.doi.org/10.2172/1257674 . Accessed 08 Oct 2020
[9] Rosenberg M (2020) The 5 Sectors of the Economy. ThoughtCo https://www.thoughtco.com/sectors-of-the-economy-1435795. Accessed 09 Oct 2020
[10] Van Nuffel L, Dedeca JG, Smit T, Rademaekers K (2018) Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? European Parliament's Committee on Industry, Research and Energy. https://www.europarl.europa.eu/RegData/etudes/STUD/2018/626091/IPOL_STU(2018)626091_EN.pdf. Accessed 01 October 2020.
[11] Ilo A (2019) Design of the Smart Grid Architecture According to Fractal Principles and the Basics of Corresponding Market Structure. Energies, vol 12, p 4153. doi:10.3390/en12214153

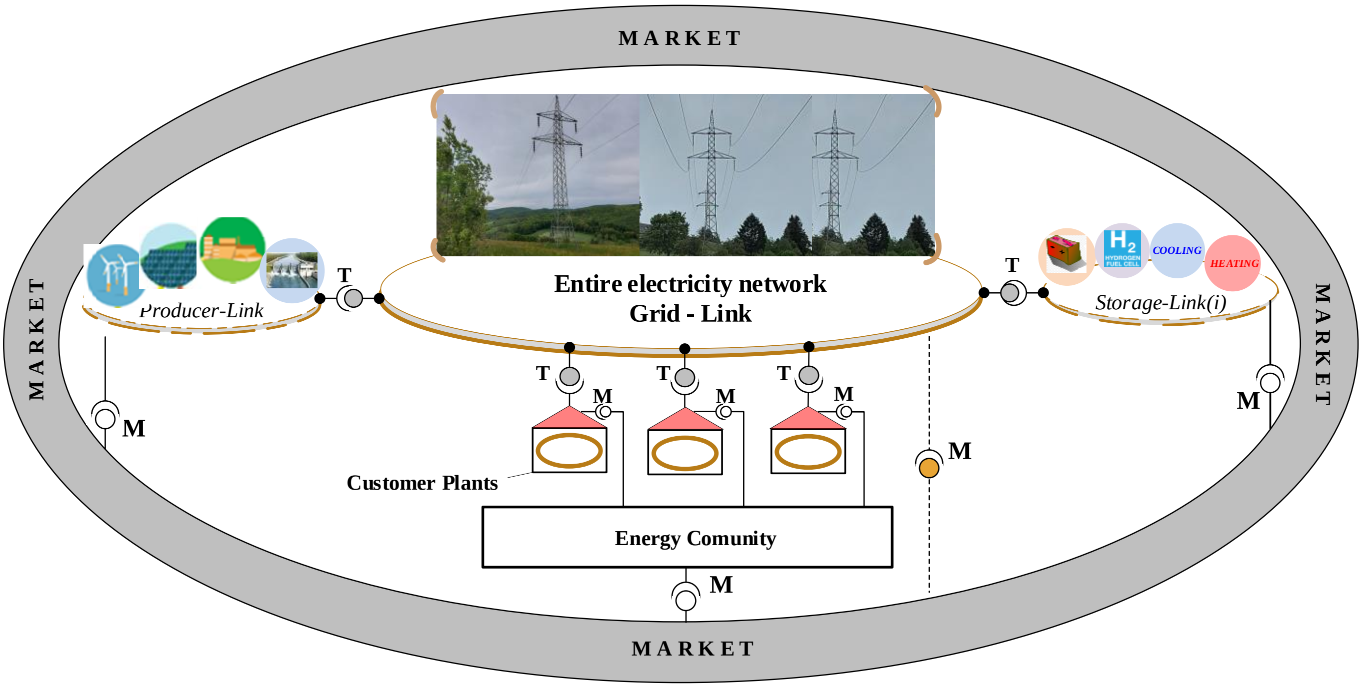

Figure 3: Overview of the holistic architecture based on *LINK*-Paradigm.

4. SECTOR COUPLING TECHNOLOGIES

4.1. Renewable power generation technologies

Renewable electricity and heat generation includes all means of generation that rely on renewable sources and energy carriers which are shortly explained in appendix A1. Solar and wind technologies have become instrumental in increasing the share of renewable energy in Europe and elsewhere, as they fulfil all environmental and societal pillars in the EU taxonomy, while their cost has also become increasingly competitive. Nonetheless, solar and wind are inherently uncontrollable sources, and do require complementing technologies (electricity storage or backup thermal power storage for longer duration) to ensure full exploitation of their production potential and to secure electric grid stability at the same time.

4.1.1. Solar based combined generation

Main technologies to convert solar radiation into electricity are direct conversion (photovoltaic systems) and conversion into heat power to be used in replacement of fossil fuels thermal power (Concentrated Solar Power – CSP). In CSP systems, large number of mirrors, or a system of lenses, concentrates solar radiation onto a receiver. CSP systems can be classified into four types, regarding the concentration technique: with linear parabolic mirrors (parabolic trough), with flat linear mirrors (Fresnel collectors), with parabolic dish (parabolic dish) and solar tower.

Design and development of plants powered by solar energy is based on simple and intuitive idea: given a fossil fuel fired power plant, to replace thermal energy released by the fuel with solar thermal energy. Most suitable thermodynamic cycles and related process fluids to set up the development of the aforementioned idea are certainly the Rankine and Brayton cycles and the most common respective process fluids, water and the air-combustion gas mixture, due to the considerable experience on power plants based on the two cycles and the deep knowledge of the thermodynamic properties of the two fluids.

CSP power plant based on Rankine cycle: Competing commercially against fossil fuel fired power plants based on water-steam Rankine cycle requires overcoming some critical issues of CSP power plant, namely, the low productivity due to the variability and intermittence of the primary source, solar radiation, and the magnitude of the plant efficiency. The plant efficiency strongly depends on the reference thermodynamic cycle. Its highest temperature value is ensured by the water-steam regenerative Rankine cycle like the equivalent fossil fuel fired boilers. To increase the CSP power plants productivity without an auxiliary fossil fuel burner system, the latest technical solution is the integration of a thermal storage system that uses an intermediate heat transfer fluid. The thermal storage system makes it possible to compensate for rapid weather fluctuations and extend the plant's operation beyond the natural limit of sunset.

CSP Power plant based on Brayton cycle: Currently, most widespread fossil fuel fired power plants based on Brayton cycle are gas turbine driven power plants whether in open cycle (without heat recovery from exhaust gases) or in combined cycle (the residual heat of the exhaust gases feeds a recovery boiler which produces additional electricity by means of a Rankine cycle). Gas turbine power plants in open cycles consume much less water than an equivalent water-steam cycle system. They are, therefore, more suitable to be installed in arid and desert places, with strong solar radiation and availability of large areas of land necessary for mirror fields. Technological feasibility of the integration of a CSP system and a gas turbine power plant, and the potential cost reduction of its electricity production was confirmed by SOLGATE [12].

[12] SOLGATE - Solar hybrid gas turbine electric power system- project [8], funded by the European Union in the period 1998-2002.

4.1.2. Geothermal based generation

The use of geothermal heat for producing electricity is a flexible way to produce a clean renewable and sustainable energy, easily transportable even over long distances and ready for use for the end-users[13]. We have witnessed within the last five years (2017-2022) a resurgence of interest in geothermal power and heat, after nearly a decade of only small development in capacity in the deep geothermal sector both for electricity and for heat supply (mainly district heating).

By the end of 2020, there were 3.5 GWe of geothermal electricity capacity in Europe, distributed over 139 power plants, corresponding more than 20 TWh of geothermal electricity produced. There are also more than 200 power projects currently under development or investigation, which means that the number of plants operating in Europe could double in the near future. Geothermal power plants have an average capacity factor that is typically above 75%, with several plants operating 100% of the hours of the year. The theoretical geothermal power potential is large and exceeds the current electricity demand in many countries. For the EU, the economic potential for geothermal power was estimated at 2 570 TWh in 2050. Results from past projects assessing its potential (GEODH and GEOELEC projects) show that geothermal energy could supply more than 10% of EU energy consumption by 2050.

Geothermal power plants across Europe are making use of widely varying geothermal resources. Most of the installed capacity across Europe, Iceland, Italy, Turkey, Overseas France (Guadeloupe), and Portugal (Azores) is deployed in high temperature markets, typically above 250°C, where geothermal power can be produced via flash or dry steam turbines, and has historically been the conventional form of geothermal power globally. Over the recent few decades, however, a new type of geothermal power markets has emerged, making use of lower temperature resources, as low as 120°C. Germany, which is the second largest geothermal power user of the European Union is typically exploiting geothermal resources of around 150°C. Hungary, Croatia and Belgium have inaugurated their first geothermal power plants.

Finally, it is to mention that 2/3 of the nowadays geothermal market is linked to the use of heat pumps under the term “shallow geothermal energy”. About 1.8 million units are installed across EU, covering a broad spectrum of applications in the residential and tertiary markets

Two conditions are necessary for the direct use of geothermal energy: the hot fluid produced via a geothermal well must have a sufficient flow rate and a temperature above a given threshold. The threshold depends on used technology, including hybrid generation. The “temperature parameter” affects the efficiency of transformation from heat to electricity, whereas the “flow rate constraint” is related to the number of wells required for a given supply threshold. The highest potential for massive supply from geothermal resources is in areas showing high temperature at relatively shallow depths (e.g. in magmatic areas, as in Iceland, Italy, Turkey and volcanic areas). However, with new technologies geothermal electricity generation will be possible everywhere, going deep enough to reach the required temperature and improving heat extraction wherever the natural flow rate proves to be too low.

Current trends in geothermal electricity generation are the following:

- Optimisation of the utilisation of geothermal resources, with a focus on increasing efficiency and reducing LCoE for low temperature binary plants;
- Improvement of the existing high temperature technologies (heat exchanger, flash/steam plants), even exploring disruptive ideas on cycle design, novel materials, and more;
- Technologies for enhancing heat extraction at depth will be optimized, proved at a large scale, and safety precautions will be standardized;
- There are plenty of technological opportunities to exploit the unique capability of geothermal energy to operate in hybrid mode with other renewable energy sources (photovoltaic, concentrated solar, biomass and biofuels) will be intensified, with an overall increase in total energy conversion factor;
- New technologies will enable us to access and manage deep and extremely hot resources, whose productivity will be ten times higher than in existing hot systems;

[13] ETIP Deep Geothermal Vision Document

- Cutting-edge technologies will be extensively assessed for producing from untapped resources that pose peculiar issues, such those off-shore, close to magma shallow intrusions, depleted or unproductive hydrocarbon fields and more.
- Geothermal energy will also play a unique role on islands and in remote areas, where its flexibility and stability can be a major asset for small local grids, solving critical problems for isolated communities.

Details about Geothermal energy as source for thermal heat are given in the appendix A1 (in particular see A1.2.2)

4.1.3. Biomass technologies

Biomass is converted into usable energy mainly through combustion. Direct combustion is the most common biomass conversion technology. The main advantage of pure or converted biomass is its storability in liquid, gaseous or solid forms, that allows for a high degree of flexibility. In fact, there are several thermal (gasification, pyrolysis, torrefaction), biological (anaerobic digestion, fermentation), mechanical, or chemical processes, through which biomass is first converted into other solid, gaseous, or liquid forms to obtain biogases or biofuels with far greater energy density and calorific value on a mass basis than the original feedstock.

70% of all EU heating is currently generated using fossil energy, but most of the existing solutions can also operate using solid, liquid and gaseous forms of biomass, possibly even without further modification. However, availability of these (bio-)fuels is limited.

Combustion of wood, residues and non-recyclable fractions of waste is implemented in Europe and worldwide at all scales. In small units at household scale, logwood, pellets and woodchips are used mainly for space heating. Larger projects up to the megawatt scale may use biomass as a single source, currently also co-combustion processes are implemented.

In **larger plants**, combustion technologies have improved fuel flexibility during the last decade. For 100% combustion of bio-residues and non-recyclable fractions of waste, Fluidized Beds (FB) remain arguably the best available technologies, ensuring top performance at competitive cost for scales as small as few MW and up to several 100s MW. Such plants can produce heat only or combined heat and power (CHP) at desirable share.

Gasification of wood, residues and wastes is a process that converts biomass- or fossil fuel-based carbonaceous materials into gases, including as the largest fractions: nitrogen (N_2), carbon monoxide (CO), hydrogen (H_2), and carbon dioxide (CO_2). This is achieved by reacting the feedstock material at high temperatures (typically >700 °C), without combustion, via controlling the amount of oxygen and/or steam present in the reaction. The resulting gas mixture is called syngas (from synthesis gas) or producer gas and is itself a fuel due to the flammability of the H_2 and CO, of which the gas is largely composed. Power can be derived from the subsequent combustion of the resultant gas, and is considered a source of renewable energy, if the gasified compounds were obtained from biomass feedstock.

Pyrolysis is the thermal decomposition of solid biomass at elevated temperatures in an inert atmosphere. However, biomass is treated at lower temperatures than in the gasification technologies. Pyrolysis is most commonly used in the treatment of organic materials. It is one of the processes involved in charring wood. In general, pyrolysis of organic substances produces volatile products and leaves char, a carbon-rich solid residue. Extreme pyrolysis, which leaves mostly carbon as the residue, is called carbonization. Pyrolysis is considered the first step in the processes of gasification or combustion. Pyrolysis of biomass is made to produce various intermediate bioenergy carriers that can be further used, e.g. for power generation, heating or for the conversion to transport fuels.

Anaerobic digestion is a sequence of processes by which microorganisms break down biodegradable material in the absence of oxygen. The process is used for industrial or domestic purposes to manage waste or to produce fuels. Much of the fermentation used industrially to produce food and drink products, as well as home fermentation, uses anaerobic digestion. Anaerobic digestion is widely used as a source of renewable energy. The process produces a biogas, consisting of methane, carbon dioxide, and traces of other 'contaminant' gases. This biogas can be used directly as fuel, in combined heat and power gas engines or upgraded to natural gas-quality biomethane. The nutrient-rich digestate also produced can be used as fertilizer.

4.1.4. Hydrogen based technologies

Gas fired CHP plants using green hydrogen instead of natural gas can be temporarily used to provide decarbonized heating and electricity as reserve capacities in a long-term seasonal view[14]. Hydrogen is a zero-carbon energy carrier that can be stored and transported[15], reduces dependence on fossil fuels[16], and is versatile to operate in transports[17], heat plants[18], industry[19] and electricity sectors[20].

In a hydrogen fuel cell engine, water and heat are the only components of the electrochemical reactions. Apart from vehicle propulsion, fuel cells have potential in various applications, such as heating and cooling, portable power, stationary electricity generation and in large electrical plants[21]. The fuel cell category depends on any elements, for example, conditions during operation (pressure, humidity, temperature), fuel cell structure (application system and scale), and the complexion of the polymer electrolyte[22].

4.2. Renewable heat and heat recovery technologies

4.2.1. Heat pump technologies

Heat pump technologies transform thermal renewable energy from a lower to a higher level. The energy used can be renewable (aerothermal, hydrothermal, geothermal)[23] or waste/excess energy from buildings, infrastructure or industrial processes. With some geographical and climatic limitations, these energy sources are available in sufficient quantities throughout Europe. Todays' heat pump stock of more than 17 million units provides a demand side flexibility potential exceeding 4 TWh per year – realising this potential needs a legislative framework that gives flexibility a value for prosumers.

Heat pump technologies have multiple benefits:

- Use of renewable energy;
- Increase the energy efficiency of heating and cooling in residential and commercial applications, industrial process and district heating. Typical efficiency factors vary between 3 and 5 for heating and 2 and 4 for cooling: meaning one unit of electricity provides multiple units of useful heating and cooling;
- Connect the heating, industrial and electrical energy vectors. The inherent flexibility stabilizes the electric grid and enables higher renewable utilization factors. Considering the capacity of industrial-size heat pumps and heat storage systems makes them important flexibility hubs for electricity grids and provide some peak shaving and load balancing to a high-RES share dominated electric grid;

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[14] "Flexible power generation in a decarbonised Europe". White Paper, ETIP SNET 2020
[15]Puduky M. et al. Renewable Sustainable Energy Rev., 30, 743–757 (2014). https://doi.org/10.1016/j.rser.2013.11.015 ; Abbasi T. et al. Renewable Sustainable Energy Rev., 15, 3034–3040 (2011) https://doi.org/10.1016/j.rser.2011.02.026
[16]Sheffield J. W. et al. Assessment of Hydrogen Energy for Sustainable Development, Springer Netherlands, 2007
[17]Coalition study, A portfolio of power-trains for Europe: a fact-based analysis, McKinsey & Company, 2010 ; J. Tollefson, Nature, 464, 1262–1264 (2010) https://doi.org/10.1038/4641262a
[18]Dodds, P. E. et al. Int. J. Hydrogen Energy, 38, 7189–7200 (2013) https://doi.org/10.1016/j.ijhydene.2013.03.070
[19]Napp T. A. et al. Renewable Sustainable Energy Rev., 30, 616–640 (2014) https://doi.org/10.1016/j.rser.2013.10.036
[20]M. Ball et al. Int. J. Hydrogen Energy, 40, 7903–7919 (2014) https://doi.org/10.1016/j.ijhydene.2015.04.032 ; S. Samsatli et al. Int. J. Hydrogen Energy 41, 447–475 (2016) https://doi.org/10.1016/j.ijhydene.2015.10.032
[21]Ajanovic, A. et al. Energy Policy 2018, 123, 280–288, http://dx.doi.org/10.1016/j.enpol.2018.08.063; Hames, Y. et al. Int. J. Hydrog. Energy 2018, 43, 10810–10821 http://dx.doi.org/10.1016/j.ijhydene.2017.12.150
[22]Salleh, M.T. et al. Polym. Degrad. Stab. 2017, 137, 83–99 http://dx.doi.org/10.1016/j.polymdegradstab.2016.12.011
[23] 'aerothermal energy' means energy stored in the form of heat in the ambient air;
'geothermal energy' means energy stored in the form of heat beneath the surface of solid earth;
'hydrothermal energy' means energy stored in the form of heat in surface water;
This has been updated in 2018/2001(still Article 2):
'ambient energy' means naturally occurring thermal energy and energy accumulated in the environment with constrained boundaries, which can be stored in the ambient air, excluding in exhaust air, or in surface or sewage water; (Source: European Heat Pump Association stats.ehpa.org)

- If 100% green electricity is used, all heat pump applications are 100% renewable and emission-free at the operation site;
- The heat pump cycle provides heating and cooling in parallel, and it depends on system design whether one or both of these services are used.

Heat pump-based solutions exist for residential (both single-family and multi-family buildings) and light commercial buildings. They also exist for industrial processes and can be incorporated into district heating and cooling systems, either as large-scale centralised solutions, or distributed at the customer side, to increase the water temperature to the level required by the user.

The efficiency of heat pumps depends on:

- The temperature difference between the heat source and the heat sink (the larger this delta T, the smaller the efficiency);
- The design of the system for single (heating or cooling) or dual service (heating and cooling) use;
- The efficiency of its components, including the refrigerant chosen;
- The smartness of controls enables the system to react to energy demands by the user.

Heat pumps can be driven by mechanical energy, produced by an electric motor (electric compression heat pumps) or a combustion engine (gas/motor driven heat pumps), or by thermal energy using the principle of sorption.

Concerning **system integration**, heat pumps provide demand-side flexibility via connected thermal storage and through the thermal inertia of the building/structure in which they operate. Operating them when surplus electricity is available and shutting them off in times of shortage allows peak shaving and load shifting enabling. Heat pumps in connection with PV are more and more supplemented by battery storage.

- Higher utilisation factors of the renewable generation assets;
- A more stable electric grid;
- More economical use of energy.

Heat pump technology is a fully recognized technology contributing to the EU's energy and climate targets. It has recently been highlighted as the leading technology to reduce fossil fuel and gas dependency. A high potential is seen by combining heat pumps with CHP technologies to respond to variable needs of electricity and heat.

4.2.2. Solar thermal technologies

Solar Thermal technologies transform solar irradiation into usable renewable heat. With the combination of a heat storage, solar thermal technologies can reliably provide cheap renewable heating throughout Europe annually.

Solar Thermal technologies have multiple benefits:

- Fully renewable technologies, are available for immediate deployment;
- The sun is an infinite source of energy, and solar thermal is scalable and efficient in all types of climates and for several different applications;
- More than 90% of the solar thermal systems installed in Europe are also manufactured in Europe with nearly fully reusable/recyclable European components;
- It creates local jobs along the value chain (including production of components, manufacturing, installation, and maintenance of solar systems);
- They have no exposure to the volatility of energy prices (gas, electricity) and do not cause an increase in electricity demand; instead it helps to shave peak power demand;
- The European solar thermal industry has a net export value of more than half a billion Euros, in certain years, more than one billion Euros.

Solar thermal technologies can both provide solar heating and cooling. The available technology capacity ranges from small domestic systems of 1.4 kW to medium-large large industrial plants of 12 MW, up to extensive district heating installations (most extensive in Europe reaching 110 MW). According to IRENA, industrial process heat accounts for more than two-thirds of total energy consumption in industry, and half of this process heat demand is low- to medium-temperatures (< 400°C). Solar thermal technologies such as Concentrating Solar Thermal (CST) can provide heating for industrial processes up to 400°C and thus cover a large portion of the global industrial heat demand.

4.2.3. Direct conversion of solar energy to heat

The main technologies to convert solar irradiation into heat are flat plate collectors, evacuated tube collectors, parabolic trough collectors and concentrated solar thermal.

The flat plate collectors (FPC) are the most common technique to collect solar energy and transform it into thermal energy. The system uses water as a heating medium and has a working temperature range between 40 - 100°C. A common application of FPC is domestic hot water preparation for single- and multi-family houses, with a typical solar fraction between 40-90% (meaning that solar energy covers these shares of the total heat demand throughout the year).

The evacuated tube collectors (ETC) consist of a number of sealed glass tubes which have a thermally conductive copper rod or pipe inside allowing for higher thermal efficiency than FPC and working temperatures between 60°C - 120°C, but up to 200°C. The ETC is mostly used in small scale applications such as space heating for single-, multi-family houses and non-residential buildings, with a typical solar fraction between 15-40%.

The parabolic trough collectors (PTC) and linear Fresnel collectors (LFC) are constructed as a long parabolic reflecting mirror, that reflects sunlight towards a heat tube, which is usually painted with a reflective silver coating, or made from polished aluminium. The metal black heat tube contains a heating medium which is pumped around a loop within the tube absorbing the heat as it passes through. The working temperatures for PTC range between 80°C - 300°C, which is suitable for higher temperature applications such as Solar District Heating (SDH) and Solar Heat for Industrial Processes (SHIP), with solar fractions of up to 50%.

4.2.4. Innovative waste heat recovery cycles

Innovative waste heat recovery cycles at low and medium temperature levels are addressed in Appendix A3. An overview is given in Figure 4.

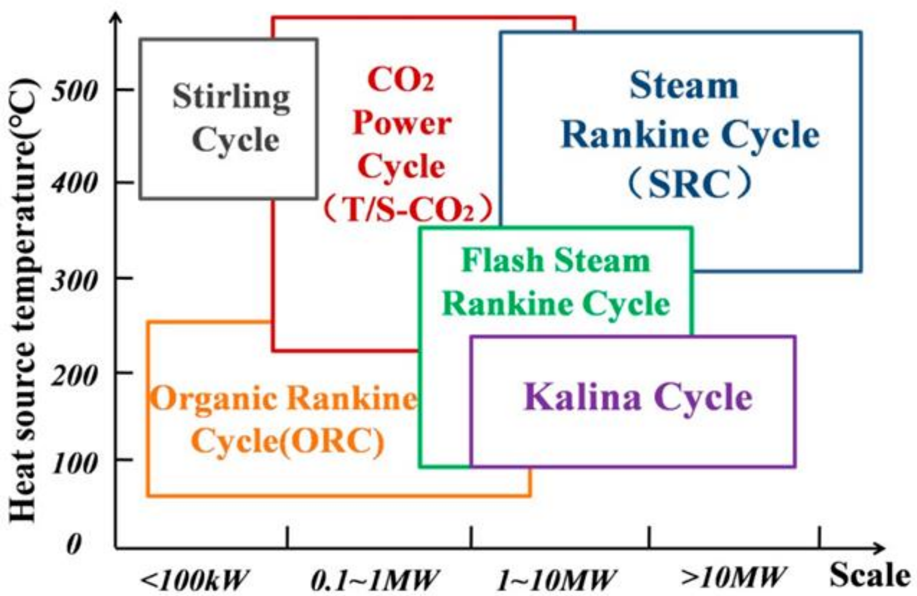


Figure 4: Waste heat recovery cycles[24]

[24] Liu, L.; Yang, Q.; Cui, G. Supercritical Carbon Dioxide(s-CO_2) Power Cycle for Waste Heat Recovery: A Review from Thermodynamic Perspective. Processes 2020, 8, 1461. https://doi.org/10.3390/pr8111461 <https://doi.org/10.3390/pr8111461

4.2.5. Direct conversion of renewable electricity into heat

Electricity generated by any kind of renewables (e.g. wind, hydro, and PV) can be converted into heat. Electrical heating devices (resistive or inductive) are examples of conversion of electricity into thermal. There is work on large scale (>100 MWth) electrical heaters that can heat up to 1000°C. With the temperature limits of heat pumps, and expensive green H_2, there is a large interest in several industrial use cases, among others cracking processes. The petrochemical industry has also recognised this, where customers are teaming up to develop e-Crackers.

4.3. Polygeneration

4.3.1. Cogeneration of electricity and heat

Cogeneration or **combined heat and power (CHP)** is the use of a heat engine or power station to generate electricity and useful heat at the same time. In terms of both efficiency and flexibility across integrated heat and power systems they bear considerable potential on the pathway towards decarbonisation in a consumer-empowering way[25]. CHP generation can be implemented at many different scales from micro-CHP to multi-megawatt CHP systems. The traditional energy sector is dominated by combustion systems that use fossil gases, oil and coal. With the steep growth of biogas plants in Europe, also biogas-driven smaller CHP systems were implemented. In addition, also wood fuelled CHP systems increase the share of renewables in the CHP sector.

Cogeneration is a more efficient use of fuel or heat, because otherwise-wasted heat from electricity generation is delivered to some productive use. Combined heat and power (CHP) plants recover otherwise wasted thermal energy for heating. Small CHP plants are an example of decentralized energy and are in use for urban district heating and industrial multi-generation facilities. By-product heat at moderate temperatures (100–180 °C) can also be used in absorption refrigerators for cooling.

Due to their high fuel conversion rates of > 85%, CHP systems fuelled by biogas/biomethane, solid biomass, green hydrogen and non-fossil synthetic fuels should be more strongly installed for power and heat generation in the transitional phase where plenty of low efficient coal-fired plants need to be replaced[26]. European manufacturers committed to delivering hydrogen-ready gas turbines and engines by 2030 to prepare them for future use in a decarbonised energy mix[27]. As reserve plants, they are assumed to provide dispatch energy during phases of low RES supply and contribute to delivering secure and affordable electricity and heat based on "green" fuels (Hydrogen, Ammonia).

4.3.2. Trigeneration

Trigeneration has been developed as an extension of the Cogeneration system and represents the simultaneous production of three "energy products": heat, electricity and cold / coolant, using a single heat source (preferable a lower or zero CO_2 emission fuel such as gas, syngas, landfill gas, LPG or petroleum gas, biomass, or solar energy as an example). Trigeneration or combined heat, power and cooling (CCHP) is thus the process by which most of the heat produced by a Cogeneration plant is used to cool the water / coolant agent/ for air conditioning or refrigeration systems. An absorption chiller is connected to the combined heat and power (CHP) plant. The "waste heat" by-product that results from power generation is harnessed, thus increasing the system's overall efficiency[28,29].

Trigeneration (or combined cooling, heat and power [CCHP] or Polygeneration plant[30]) is the process by which some of the heat produced by a Cogeneration plant is used to generate chilled water/refrigeration agent/ for air conditioning or refrigeration. An absorption chiller is linked to the combined heat and power (CHP) to provide this

[25] "Towards an efficient integrated and cost-effective net-zero energy system in 2050: the role of cogeneration", Artely power point presentation, 2020 artely.com
[26] "EU drafts plan to label gas and nuclear investments as green", https://www.reuters.com/markets/commodities/eu-drafts-plan-label-gas-nuclear-investments-green-2022-01-01/
[27] Gas turbines – driving the transition to renewable-gas power generation,EUTurbines 2019, (www.powertheeu.eu)
[28] http://en.wikipedia.org/wiki/Trigeneration
[29] https://www.edina.eu/power/trigeneration-cchp
[30] https://www.clarke-energy.com/trigeneration/

functionality. Quadgeneration extends this process further by adding systems to purify carbon dioxide from the engine exhaust. Combined cooling and power (CCP) are plants where electricity and cooling are utilized alone.

Combining a Cogeneration plant with an absorption chiller makes it possible to use the surplus of seasonal heat for cooling. The boiler cooling circuit's hot water acts as the chiller's primary energy source. At the same time, the hot exhaust flue gas can also be used as an energy source for steam production, and as an energy source for a high-efficiency absorption chiller. Thus, up to 80% of the thermal energy of the Cogeneration plant can be transformed into chilled water/cooling agent/, depending on the chiller's efficiency. This way, it is possible to use its capacity throughout the year and the overall efficiency of the Cogeneration plant can be significantly increased.

Figure 5 shows the schematic of the energy flow.

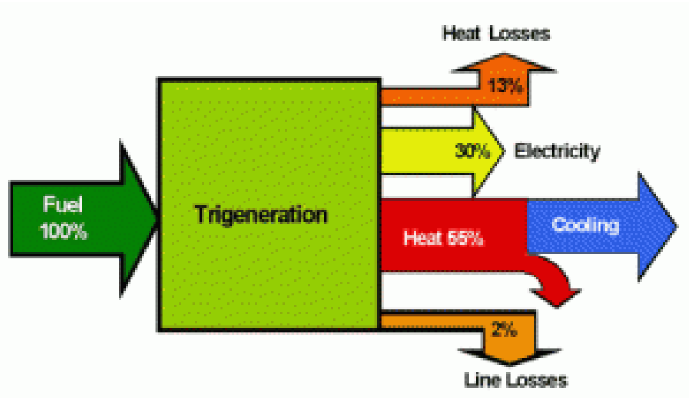


Figure 5: Example of the schematics of the energy flow for Trigeneration systems[31]

4.4. District heating

In district heating and cooling (DHC), heat or cold is supplied from large to medium-scale generation facilities to multiple private or commercial users through a network of pipes, mostly water or steam. Thermal generation facilities are typically combined heat and power (CHP) plants that use fossil energy, biomass and biogas or municipal waste, geothermal, solar and wind or industrial waste heat. DHC systems are built on very mature technologies used in many countries over the last decades. They operate at a high energy utilisation level, since most users typically only require heat at low temperatures, which can be provided by CHP plants very efficiently. Therefore, DHC systems are contributing to significant energy savings and carbon emission reductions. The ongoing deployment of enormous capacity, high-temperature heat pumps in district heating, and cooling grids helps further to decarbonise these.

DHC systems can take a central position in coupling different energy sectors. They already co-generate heat, cold, and electricity nowadays, and many DHC networks are also using thermal energy storage to decouple heat and power generation, which provides additional flexibility. Additional potential for sector-coupling is offered by using "Power-to-Heat" or "Power-to-Cold" technologies, in which surplus electrical power from renewables is converted into heat and utilised in the DHC system, to avoid curtailing renewable electricity . Due to their access to low-cost power that is often produced just as a "by-product" in the CHP plants, DHC operators are also considering hydrogen generation for the mobility sector at their facilities[32].

While some countries, particularly in Scandinavia, show a significant penetration of district heating of over 50% of the heating market, district heating has only a small share (approximately 12%) of the total heat market of the EU[33].

[31] https://www.clubafaceri.ro/4915/trigenerare---cu-echipamentele-de-cogenerare-18563.html; https://www.clubafaceri.ro/4915/b-team-consult-and-services-srl.html
[32] https://www.zak-kempten.de/download/lz-08.08.2020-seite-1.pdf
[33] District Heating and Cooling: Environmental Technology for the 21st Century (IEA DHC (iea-dhc.org) Policy Paper)

5. STORAGE AS SECTOR COUPLING DEVICE

Integrating high amounts of intermittent renewable energy sources such as wind and solar in the power grid poses problems in terms of power balancing, and grid operators face the challenge of matching supply and demand. Besides using system flexibilities, the main solution to these challenges is introducing more storage systems, which requires significant investments. Electricity is hard to be stored directly on a large scale. Therefore, it needs rather to be transformed into mechanical, thermal or chemical vectors. Storage includes direct electric storage systems, as well as conversions (possibly bi-directional) including Power-to-Heat and Power-to-X processes, biomass and intermediate bioenergy carriers, which are storable, and on-demand. They can be used in combined heat and power (CHP) plants to supply electricity if required. For example, it is expected that the storage capacities have to be increased by 2 to 3 orders of magnitude to avoid curtailing future on- and off-shore wind park operation[34].

Nowadays, pumped storage covers more than 90% of stored electricity in the EU[35] but is limited in expansion due to regional and environmental restrictions. For long-term storage focus will be on the chemical (Power-to-gas) to enable storage capacities at large scale which will be essential for renewable electrification of all energy sectors[36], Fig. 6. In particular, preferably in the short and medium term for the coupling of energy and heating and cooling sectors, thermal storage can play an important role where electricity is converted into heat and cold to be later discharged either to the electricity grid (i.e. via steam cycles and ORC processes) or to the heating and cooling infrastructure. Examples are the Electro-thermal energy storage (ETES) cycle[37] or the European project TESSe2b[38]. In the meantime, solar district heating systems in Denmark come with thermal storage in the range of 10-20 GWh (>200.000 m^3 water).

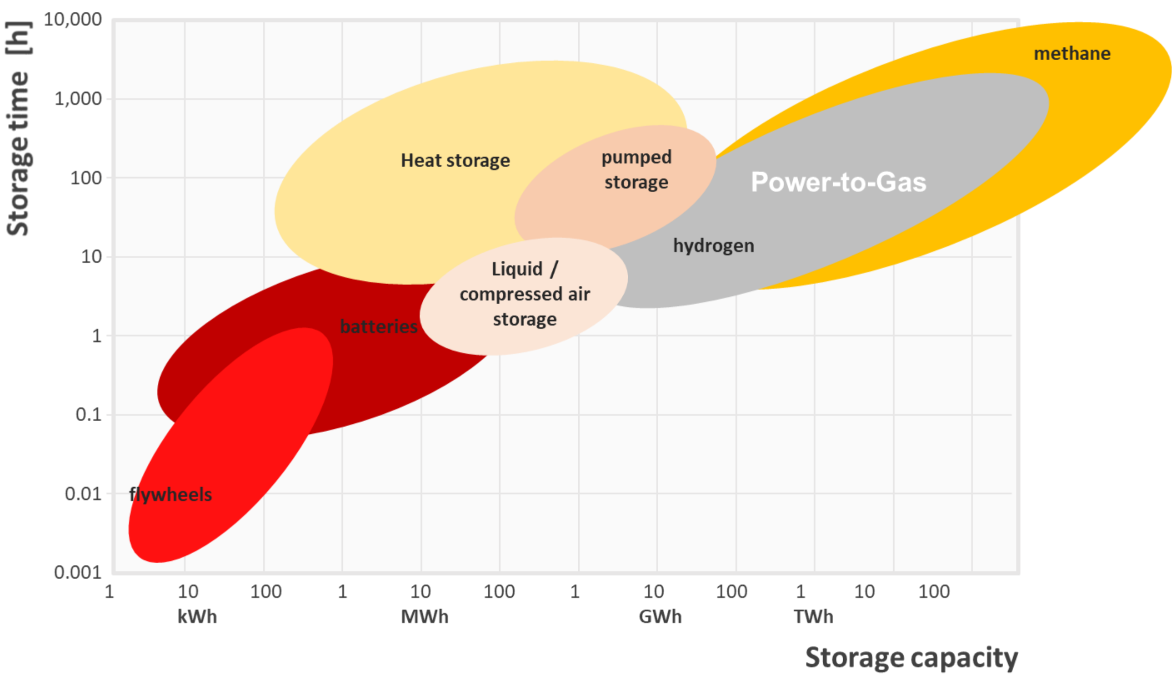


Figure 6: Storage devices in size and storage time[36]

[34] ETIP SNET WG 3 Webinar: "Flexible generation in a low-carbon RES dominated energy system" on 30th June 2020
[35] REN 21: renewables report
[36] K.Görner: Sector coupling as a chance of power generation, Trends. Aachen 2017
[37] MAN ETES Electro-thermal energy storage. MAN Energy Solutions, 2021
[38] TESSe2b - Thermal Energy Storage Systems for Energy Efficient Buildings. An integrated solution for residential building energy storage by solar and geothermal resources EU Horizon2020 GA ID: 680555, 2019

The fundamental principle of thermal storage is to utilise the thermal capacity of an object (piece of material, device, or closed space), which characterises the amount and speed of energy exchanges with the surrounding environment, depending on their temperature difference.

If the aim of the heating/cooling process is to control the object's temperature, its **thermal inertia** (intrinsic time-lapse in response of temperautre vs heat exchange) can be exploited to modulate the load profile of the energy exchanged for heating/cooling; typical example are residential and service buildings. Such modulation is a flexibility option for the supplying system, usually requiring no or little additional investments.

If instead the object is built on purpose to store thermal energy, it represents a **pure thermal storage** device, to be operated according to energy system needs, and to be assessed through a cost-benefit analysis of its investment+operating costs vs the benefits it brings to the system (typically, the different time-value of the energy input and output).

The following examples highlight storage systems that have direct impact on the electrical and heat grid systems.

Thermal energy storage can provide sector integration in the following ways:

1) With so-called Carnot Batteries, electricity is used to charge a thermal energy storage (thermal battery), e.g. via resistance heating. The heat is stored either sensibly at a high temperature in a solid (stones, concrete, sand, etc.) or in a PCM (salt, metals) or in a TCM (metal oxide-hydroxide reaction or other). After the storage period, the heat is used in a power cycle to generate electricity (Power to heat to power). An essential role for solar heat to power is storage for CSP, concentrated solar power. Electricity dispatch is enabled here with molten salt thermal storage, molten metal, or high-temperature solids thermal storage. (RES to power).

2) Another option: surplus electricity is stored in a thermal storage device (in similar ways as described above) and the heat (or cold) stored is used when heat (or cold) is needed locally or in a district heating network. The storage technologies used are in sensible heat using water or directly underground. In addition to this more than 95% of the storage market (i.e. water-based heat storage), new developments are on the market using molten salts, metals or thermochemical heat storage by zeolite materials. Water storage is by far the most common technology in H/C plants. This is due to several reasons:

- Water is commonly available in large quantities;
- Water is cheap;
- Water has a very high thermal capacity and can therefore store large quantities of heat in relatively limited volumes;
- Water is harmless.

Due to the nature of renewable energy sources, any RES H/C system relies on thermal storage to match energy availability and demand.

3) In the case of solar thermal plants, heat is stored during sunny hours. In contrast peak heating demand occurs in the early morning or later evening (depending on the type of use, whether heat is used for domestic hot water or for space heating).

4) Biomass boilers need thermal storage to ensure every fuel load is exploited in the best possible way, independently of the instantaneous heat demand.

5) Heat pumps also rely on thermal storage to avoid oversizing the device: smaller devices are cheaper and operate more often throughout the year at nominal working conditions, thus being more cost-effective than oversized devices.

6) DH networks use thermal storages to avoid peak loads (and thus the use of mostly fossil-based peak load boilers), to optimize the operation of CHPs or heat pumps on the electricity markets, and to integrate fluctuating

renewables (i.e. solar as mentioned above) or waste heat[39].This enables a higher degree of freedom for planning and operation of the energy system, a high level of security of supply, system stability and flexibility[40].

7) In the coupling between electricity and gas grids, waste heat is generated in the transformation processes that can be stored: this applies both for electrolysis (mostly large scale) and fuel cells (both large scale and small scale distributed). For solid-oxide fuel cells (SOFC), the storage temperature is high (500 °C or higher), while for proton-exchange membrane fuel cells (PEMFC), temperatures are below 100 °C.

The size of **water-based thermal storage** varies enormously across different applications of RES H/C systems. For single-family domestic applications typical sizes range from a few hundred litres to a few cubic meters (few kWh up to hundreds of kWh). For large multi-family buildings, storage can be as high as several cubic meters and up to dozens (few MWh). RES H/C systems for industrial processes may need up to hundreds of cubic meters (dozens of MWh) of thermal storage. Finally, in district heating systems water storages of thousands of cubic meters can be easily found (hundreds of MWh). Recent large solar thermal district plants in Central and Northern Europe (especially in Denmark) use storage of hundreds of thousands of cubic meters (> 10 GWh).

Due to the large availability of such water-based thermal storages, sector integration between the electricity and the H/C sector will have to address more and more of those devices. Even tiny storage, if aggregated, represent a high potential for flexibility.

A rough calculation based on currently installed solar thermal plants at the European level shows that a storage capacity of approximately 150 GWh is currently established for this technology alone.

IRENA[41] estimated the total installed capacity worldwide of thermal energy storage for heating applications installed in 2019 to be roughly 200 GWh. Of this capacity, 46% is installed in buildings and 53% operates in district heating networks (half of this being seasonal storage).

Looking at the space cooling application, almost 15 GWh of thermal storage was installed in 2019.

8) Electro-thermal energy storage is a large-scale Trigeneration energy storage and management system for the simultaneous storage, use and distribution of electricity, heat and cold.

Ground-based energy storage can provide sector integration, too:

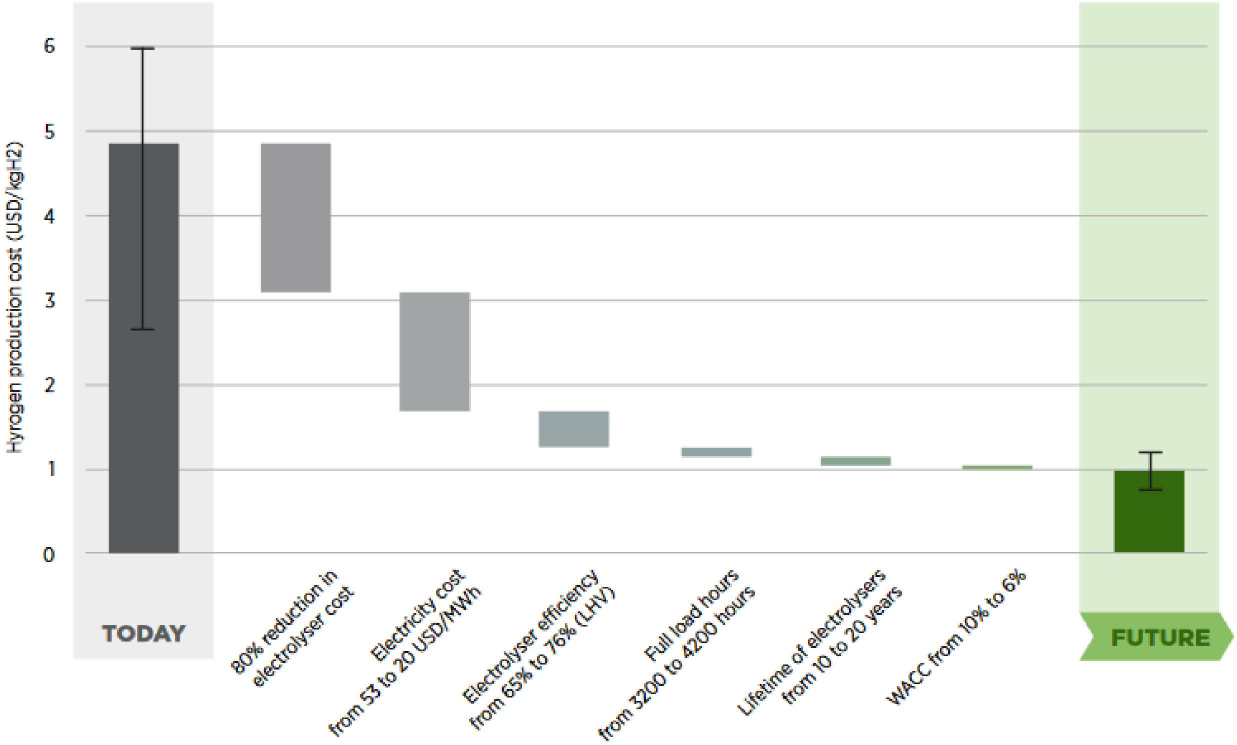
Shallow geothermal energy: Energetically, a pump-based shallow geothermal resource is a conversion of electric energy into a much larger heat flow. It is exegetically poor, but superior to other conventional conversion technologies, like air-source of direct electricity-heat conversion due to its higher efficiency. The heat produced is stored in the ground or extracted, creating a temperature change that can be used for further applications. Examples are given in appendix A5.

Deep geothermal energy: Deep geothermal energy is essentially heat stored previously in the ground by natural conduction/convection processes operating at high depths. The extracted temperatures can be as high as to produce electricity. Through reinjection, required to keep the production of the extraction wells, it is possible to interact with the reservoir, which is used as storage in the first pilot plants

Power-to-gas, Hydrogen: Within the EU hydrogen strategy, several research projects both within industry and government exist. Market readiness for "green" hydrogen production is expected well before mid-century along with the expected decrease in renewable energy production costs, Fig. 6. If large quantities of hydrogen become economically viable, it can replace fossil fuels in thermal and gas driven combined/cogeneration back-up plants in the future. Currently, the integration of hydrogen production into a gas turbine-driven CHP plant for an industrial

[39] https://www.iea-isgan.org/wp-content/uploads/2019/06/Energy-Storage-Systems-ESS_Casebook_Final-1.pdf
[40] https://doi.org/10.1016/j.egyr.2021.09.040
[41] Innovation outlook thermal energy storage, IRENA, 2020

application (paper and pulp industry) is demonstrated in the EU HORIZON2020 project HyFlexPower[42]. CHP use is currently planned in the Vienna district heating network[43].



Note: 'Today' captures best and average conditions. 'Average' signifies an investment of USD 770/kilowatt (kW), efficiency of 65% (lower heating value – LHV), an electricity price of USD 53/MWh, full load hours of 3200 (onshore wind), and a weighted average cost of capital (WACC) of 10% (relatively high risk). 'Best' signifies investment of USD 130/kW, efficiency of 76% (LHV), electricity price of USD 20/MWh, full load hours of 4200 (onshore wind), and a WACC of 6% (similar to renewable electricity today).

Figure 7: Costs of green hydrogen production[44]

Biomass as a reserve energy resource: biomass is an important renewable energy source that can be relatively easily stored over long periods and used on demand. This is the case of traditional biomass use in the heating sector, where wood is harvested, dried, stored and used during the heating season. It applies of course to wood used in CHP systems. In addition, also digestible biomass can be stored (e.g. as silage) and used on demand, e.g. through biogas plants. Modern biogas plants, that produce heat and power can significantly contribute to balancing the power grid by switching on and off their gas engines in a short time, depending on signals from the power grid. For this, a gas storage acts as a buffer. The storage capacity ranges from a few hours to a few days but is usually used for balancing the intraday power demand.

CAES/LAES

Compressed air energy storage (CAES) or liquid air energy storage (LAES) are additional energy storage technologies related to the converting electricity into heat or cold, and vice versa. In CAES systems, electricity is used during the charging process to compress ambient air to high pressures of up to 100 bar. The compressed air is then stored in a gas storage, typically an underground cavern. The energy stored in the form of pressurised air can be reconverted to electricity by expanding it in a piston engine or turbine during discharge. Since conventional CAES systems do not store the heat generated during compression, heat needs to be added again in this step. This

[42] HyFlexPower, - HYdrogen as a FLEXible energy storage for a fully renewable European POWER system,LC-SC3-NZE-4-2019
[43]https://www.wienenergie.at/pressrelease/gruenes-kraftwerk-weltweit-erster-wasserstoff-betriebsversuch-in-wiener-gasturbine-geplant/
[44] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency, Abu Dhabi
https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

is typically done by combustion of natural gas, which could also be replaced by hydrogen. More advanced, so-called adiabatic CAES systems also store the heat generated during compression in a thermal energy storage material such as ceramics, concrete or natural rock, often at temperatures above 600 °C. While this stored heat could be used later on as thermal energy, it is usually taken for heating the pressurized gas during discharge, before it expands in the piston engine or turbine. This improves the overall storage efficiency.

In contrast, LAES systems use electricity during charging to power an air liquefaction plant that produces liquid air, which is then stored in an insulated tank at low pressure. During discharge, the liquid air is pumped to high pressure, where it is evaporated. This gaseous air can be used to drive a piston engine or turbine to generate electricity. The compression heat and the expansion chill can be stored and recovered to improve the round-trip efficiency. Moreover, the same storage can be used to recover waste heat and chill from external operations, boosting further the return of electricity.

More recently, there has also evolved a novel technology (Energydome)[45], which is based on the same thermodynamic principle as CAES and LAES, however in this case it resorts to CO_2. This technology has some promising advantages, as all the process is done at ambient temperature. While charging, the CO_2 is drawn from the atmospheric gasholder, compressed and stored into high density, supercritical or liquid state at ambient temperature. When discharge is needed, the compressed CO_2 is evaporated and expanded into a turbine, generating electricity and returned to the atmospheric gasholder. The use of CO_2 allows the system to be more compact, having a high energy density. CO_2 could come directly from the atmosphere, contributing to the carbon capture.

[45] https://energydome.com

6. R&D NEEDS AND CHALLENGES

6.1. Sector coupling components

6.1.1. Solar and Concentrated Solar Power (CSP)

This section describes the most urgently needed Research and Innovation (R&I) activities to enhance sector coupling capabilities in Solar and Concentrated Solar Power (CSP) plants:

Solar District Heating (SDH) networks

- Integration of large solar thermal systems and storage DH networks
- Developments in system components, involving performance, price, and reliability. Improved technical aspects related to the design and operation of large SDH systems,
- Changing district heating systems from single source boilers with controllable fuels to multi-renewable supply systems
- Tackling non-technical issues, including environmental impact assessment, improvements in the fields of area screening and development or land availability

Solar Heat for Industrial Process (SHIP)

- Standardization and modularization
- Integrated solutions for processes below 100°C
- Integrated solutions for processes between 100-400°C
- Foster sector coupling, maximising the potentially suitable hybrid storage (supplied by various heat sources at different temperatures) and sector-specific measures of thermal load shifting
- Integration of SHIP urban planning concepts, processes, guidelines and local energy roadmaps.
- Long-term, third-party verified performance data projects
- Thermal collector and storage development, to reach higher solar ratios in largescale industrial projects and new storage technologies
- Emerging process technologies, namely new technologies providing the usage of low-temperature heat

Solar thermal applications in buildings

- Hybrid solutions, including new thermal energy storage concepts and combination with other technologies, as well as photovoltaic thermal collectors (PVT)
- Improved hybrid collectors, such as PVT (photovoltaic and thermal) and new collectors with temperature-controlled performance.
- Improved retrofit solutions and renovation technologies, including enhanced and simplified integration with other heating solutions
- Developing prefabricated multifunctional solar facade systems.
- Developing smart systems based on simplified design, cost-efficient components, and optimised control strategies, which provide good system efficiency at lower costs and improved reliability on installation and operation.
- Developing 'Solar-Active-Houses' with high solar fraction.
- Maintenance and performance through reliability, data gathering and IoT.
- Increase simplicity of installation with intelligent and cost-efficient components and intelligent controllers for system surveillance and diagnosis.

CSP Plant thermodynamics and operation:

- Advanced concepts for optimised operational flexibility using state-of-the-art technologies (e.g. artificial intelligence, machine learning, digitalisation)
- Development and holistic optimisation of an advanced CSP cycle and power block featuring a steam turbine with elevated steam pressures (e.g. supercritical) and steam temperatures (≥600°C)
- Development and holistic optimisation of an advanced CSP cycle and power block supercritical CO_2 turbine as a working fluid

CSP Plant components:

- Plant component improvements: expansion of turbines and technologies for modern CSP
- Cost-effective and oxidation-resistant alloys by extending the application of steel to higher temperatures (e.g. up to 650°C)
- Advanced sealing technologies – e.g. quasi-hermetic shaft seals
- Development of supercritical steam turbines for CSP
- Robust large last stage blades maximising efficiency – e.g. improved air foil design, novel damping technologies
- Development of a supercritical CO_2 turbine for CSP

6.1.2. Heat pumps running on renewable electricity

For most application areas market-ready solutions exist. However, research is needed concerning

- improved product performance,
- reduced (system) cost,
- reduced product size and footprint to open application areas with limited space,
- enhanced application areas,
- enlarged application envelope to achieve higher / lower temperature levels,
- improved interfaces to the electric grid/building energy management,
- hybrid solutions integrating them with other renewable energy technologies,
- standards and building codes as well as
- mass deployment including new business models.

Additional research is needed concerning the challenges related to directly coupling heat pumps with RES electricity:

- Coupling HP with direct current (DC) from local PV plants (or small wind turbines);
- Increasing temperature delivered by HP, to cover a wider range of applications (e.g. industrial process heat).

The necessary R&D for industrial heat pumps concentrates around the increase of delivery temperatures to at least 250°C and the scale up to the systems to cover industrial sites with MW-scale heat consumption. With this scope in mind, the heat pump R&D community works on the following topics:

- New working media and natural refrigerants that will allow semi-conventional heat pumps cycle to cover this temperature range;
- Novel heat pump thermodynamic cycles;
- R&D on compression technology to increase the delivery and operating temperature;
- Modularization of the technology to reduce heat pump installation cost;
- Business plan innovation for integrating high-temperature heat pumps in industrial users;
- Entire electrification strategies of industrial sites

6.1.3. Biomass driven CHP systems

As described above, CHP systems which use biomass can differ in size (micro-scale to multi-Megawatt scale), technology (e.g. steam turbine, biogas engine, ORC, Stirling engine) and use biomass (woody material, digestible material, oils). Depending on whether CHPs are mainly heat-driven or power-driven systems and especially on the size of the CHP plant/unit and on the utilized biomass, their role in the power and heating sectors can differ tremendously. For example, biogas engines are very flexible and can be switched on and off in a very short time, this activity contributes to stabilising the power grid. On the contrary, traditional and fossil fuel-driven large-scale power plants were mainly used in the past for base load power generation as they are by far less flexible.

Research is needed on the best integration of different sizes of CHP systems in the power grid, by maximizing the use of the heat simultaneously. For various applications, innovative concepts are needed that benefit from a maximum heat and power efficiency. The applications can be based on the power and heat demand at household scale up to district scale, but also at smaller to larger industrial scale. It is necessary that CHP systems on the one hand contribute to power grid stability, on the other hand provide heat on demand and reduce the amount of so-called “waste heat”. To achieve this, integrating different storage systems may also contribute to increase the overall efficiency.

6.2. Heat and power demand management

This chapter deals with the potential of excess/waste heat, power-to-heat and the role of hydrogen in the decarbonisation efforts. Focus will be in the outline of the most necessary R&I needs to foster the coupling of electricity and heating/cooling sectors.

6.2.1. Industrial heat and power

Major research topics are related to the temperature levels of waste heat and are as follows:

- Thermal energy upgrade by increasing size (MWth) and output temperature above 200°C and 250°C in industrial heat pumps;
- Scale up and down of low temperature (100-350°C) waste heat to power cycles (ORC, TFC)
- Demonstration of s_{CO2} cycles at a wide variety of temperatures (200-600°C) and subsequent scale-up;
- Development and demonstration of waste to cold technologies;
- Development of hybrid systems (from different renewable heat sources) to a flexible combined generation of heat and power;
- Development of grid-friendly loads (provision of frequency support – inertia).

The specific challenges are: better use of process excess/waste heat represents a significant source of energy savings for industries. In the context of reducing greenhouse gas emissions and introducing the concept of circular economy in heat management given industrial process electrification, European industries have a clear interest in finding new ways to use the heat produced by their process and to reuse it or produce electricity. The conversion of excess heat back to electricity would also improve energy efficiency, mitigate the increase of electricity consumption due to industrial electrification and thereby reduce the load on the power grids. This will also facilitate balancing the grid due to the intermittent electricity supply from renewables. In cases where electrical recovery of waste heat is not feasible, the energy should be recovered by DHC networks and used to supply heat to nearby buildings.

Innovative heat to (mechanical or electrical) power conversion using organic or supercritical CO_2 cycles, presents several benefits compared to conventional steam cycles. While organic cycles have the potential to recover low-temperature heat, the supercritical CO_2 cycle covers medium and high temperatures with drastically reduced footprint, higher efficiency reduced or eliminated water requirement, and reduced operational costs.

These technologies are also transferable to power generation: (bio)gas, geothermal or concentrated solar power, etc., with higher efficiency than established technologies.

In order to reach this goal, the following development areas need to be covered[46]:

- Optimisation of thermal cycles for different exhaust temperature levels and constrained industrial environment, in terms of efficiency and economics (CAPEX, OPEX);
- Development of design tools at components and system levels;
- Development/improvement of materials and components: heat exchangers, turbomachinery, waste heat recovery unit, power generator and electronics, etc.;
- Integration and demonstration of the system in an industrial environment;
- Assessment and dissemination of the technical and economic benefits.

Given the transversal nature of the technology, the potential for transferring the technology to the generation of small power electricity with better efficiency should be assessed and disseminated.

- Improved cycles to achieve higher levels of efficiency, higher cost-effectiveness, and wider input temperature ranges, allowing heat recovery from more industrial processes;
- Significantly reduced system size compared to steam turbines, making them suitable for installation next to the industrial process;
- Assessment of cross-sectorial applications to several types of thermal power plants (e.g. Concentrated Solar Power, biomass, geothermal, etc.);
- Primary energy savings (GWh/year) in the industry (heat recovery) and potential savings in the power generation sector;
- GHG emission reductions (tCO2-eq/year) in industry.

6.2.2. Power to heat

Power-to-Heat (PtH or P2H) is a new name for converting of electrical energy into heat. This can be done through conventional heating resistors, electrode boilers and heat pumps.

The purpose of PtH systems is to utilize excess electricity generated by intermittent renewable energy sources (solar, wind) which would otherwise be wasted. Thereby heat generated with electricity can displace fossil energy and reduce emissions in the heating sector. In contrast to simple electric heating systems such as night storage heating which covers the complete heating requirements, Power-to-Heat systems are dedicated systems to utilize excess electricity of the power grid, thus stabilising the grid. A heating system is not used as a single device, but as one heating source in combination with other heating sources, such as wood combustion systems. When there is excess power in the grid, the heat production can result from electric energy, otherwise the traditional heating system will be used. To increase flexibility Power-to-Heat systems are often coupled with buffer tanks and other heat storage.

Research is needed on the integration of PtH systems in different power grids of different countries in Europe. The European power grids are currently very diverse in the shares of renewable energies and the composition of power generation is constantly changing. This needs to be considered. It further needs to be investigated how much and at which scale PtH systems could contribute to future power and heating systems.

6.2.3. Usage of hydrogen as future energy carrier

Hydrogen will play an important role as future energy carrier in sector coupling strategy. The following R&I measures to raise the viability for the electricity and heating/cooling networks:

Replacement of fossil fuels and plant considerations: Due to the high adiabatic flame temperature and flame speed of hydrogen, existing burner systems for hydrogen-enriched fuels need to be further developed to comply with the lowest emissions limit values and to enable safe operation (avoidance of high flame temperatures and flame flash back). This is one of the most urgent R&I needs to be addressed short-dated. Furthermore, for a

[46] A more comprehensive description is available as „strategic research and innovation agenda for heat pumps“ https://www.rhc-platform.org/sria_heatpumps”

fuel switch, flue gas cleaning systems must be retrofitted during plant conversions. Research is needed for safety-related systems, material selection and seals which must be adapted to the changed conditions.

Creating Hydrogen infrastructure: Hydrogen for large-scale application does not yet have a suitable infrastructure except for big chemical clusters where fossil fuels-based "grey" hydrogen is already distributed on a GW scale to refineries, fertiliser plants and other users in pipeline systems (e.g. in the chemical industries in the western part of Germany and the Rotterdam area in the Netherlands). Consequently, this infrastructure is considered as the entry point for large electrolysers up to 10-100 MW. These electrolysers should also serve grid balancing and avoid curtailment of RES.

6.3. Storage from an energy system integration view

Nowadays, electricity storage technologies are undergoing an intensive development process. They are available in different sizes and can be integrated into any grid voltage level to balance the electricity power surpluses provided in the case of volatile renewable sources (solar, wind, etc.). Combining energy systems through sector coupling, including Power-to-Heat and Power-to-X solutions, offers enormous storage potential and contributes directly to the decarbonisation of the economy.

Power-to-Heat and Power-to-X solutions claim only the electricity surplus and, consequently, can be considered as a storage solution from the point of view of the power grids. Traditional power system theory treats storage as part of power plants, which seems out of date because, among other things, it cannot be used to describe P2X processes. In the holistic *LINK*-Solution, storage is perceived as one of the new architecture's main components. Coupling components, such as pumps, fuel cells, anode and cathodes (for batteries), heaters, and so on, convert the electricity surplus into other energy forms to be stored and reconverted into electricity at another point in time (bi-directional energy conversion) or to be consumed further[47]. These coupling components are known as electricity storage units.

For transparent monitoring of storage and its appropriate consideration in algorithms of various management system applications used in power grids, the Storage-Link (a composition of the storage facility, its primary control, and the interface) is classified into three categories, Table 1. In **"Cat. A"** the stored energy is injected at the charging point of the grid, such as pumped hydroelectric storage, stationary batteries, etc. In "**Cat. B"** the stored energy is not injected back at the charging point on the grid, such as Power-to-Gas (P2G), batteries of e-cars, etc. And in "**Cat. C"** the stored energy reduces the electricity consumption at the charging point shortly, such as cooling and heating systems (consuming devices with energy storage potential).

Table 1: Storage categorisation from the perspective of the power grid

Storage-Link category	Description
Cat. A	The stored energy is injected at the charging point of the grid.
Cat. B	The stored energy is not injected back into the charging point on the grid.
Cat. C	The stored energy reduces the electricity consumption at the charging point in the near future

Fig. 8 shows the integrated energy systems through sector coupling, as given by the holistic *LINK*-Solution. The coupling through the electricity, gas and thermal networks is realised through the coupling components such as:

- Electrolysers and fuel cells between the electricity and gas networks;

[47] A. Ilo, D.L. Schultis „A Holistic Solution for Smart Grids based on LINK– Paradigm", Springer Nature Switzerland, 2022, XVIII, 348. ISBN 978-3-030-81529-5

- Heat pumps through the electricity and heat networks;
- While the coupling through the gas and heating networks realises through, e.g. the gas condensing boilers and CHPs.

The conversion between the electricity, gas and thermal networks occurs through the PtG and PtT processes. At the same time, the conversion process between the gas and heat networks occurs through the GtH process.

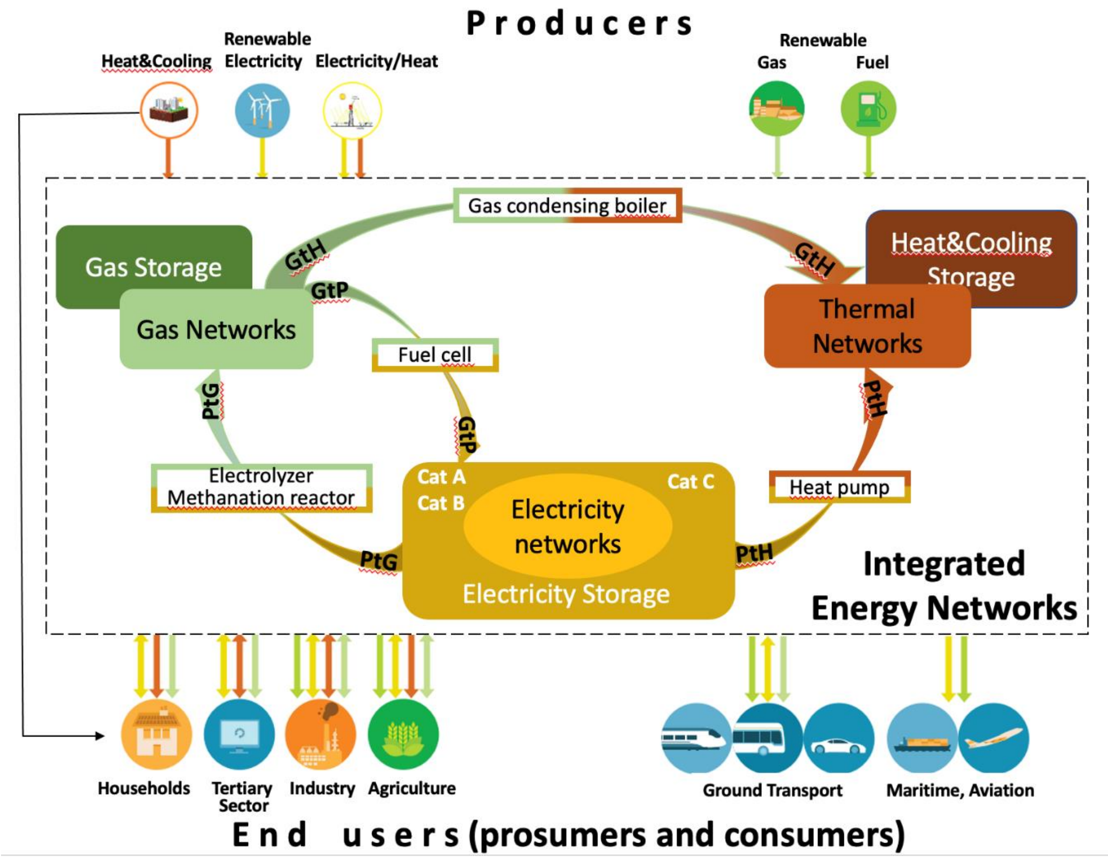


Figure 8: The integrated energy systems through sector coupling, as given by the holistic *LINK*-Solution

According to the *LINK* holistic approach, several conversion stages may exist in the landscape of integrated energy systems. Fig. 9 shows the diverse conversion stages in coupled cross vectors of electricity and thermal (heating and cooling). Three conversion stages are identified as follows:

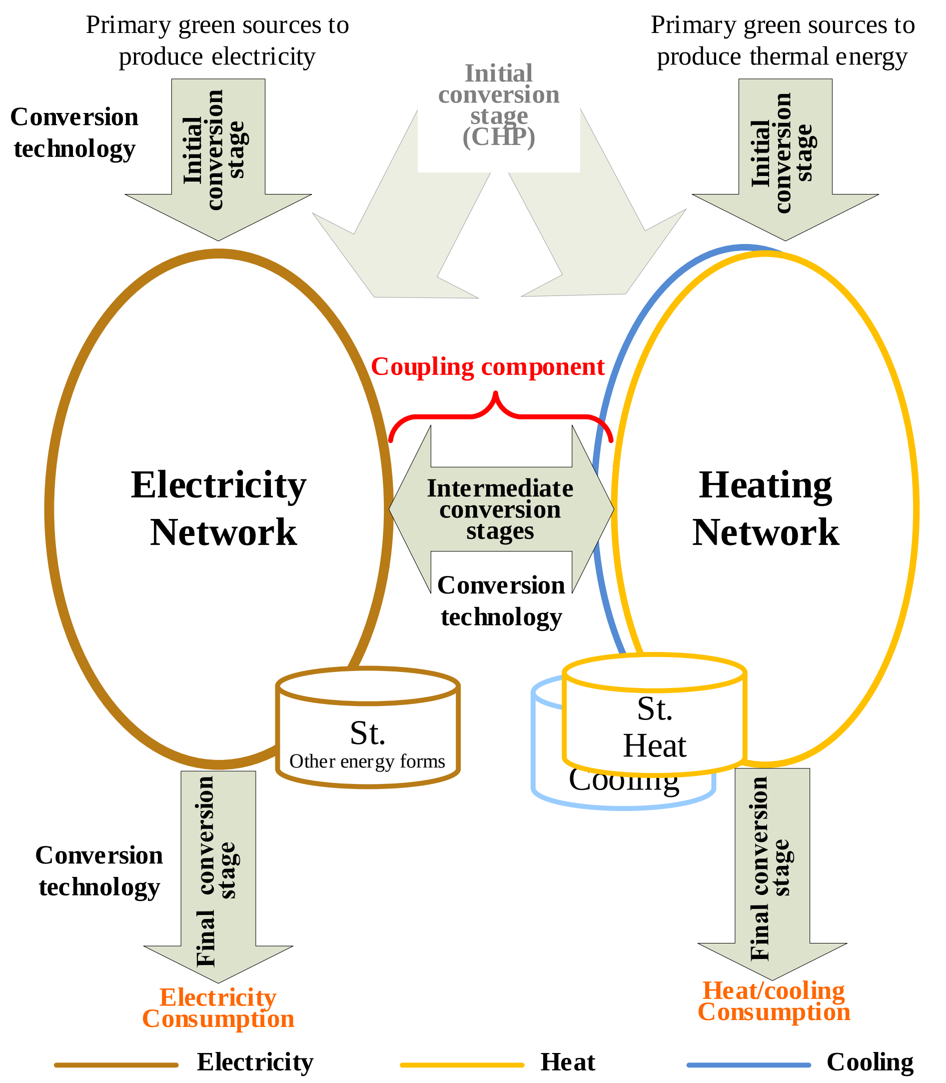


Figure 9: Diverse conversion stages in coupled cross vectors of electricity and thermal (heating and cooling).

<u>Initial conversion stage:</u> This conversion stage includes the conversion process from the primary energy resources, such as solar, biomass, etc., to the energy carriers, electricity or heat or cooling. The conversion process usually occurs through different producers' technologies such as generators, CHP, etc. CHPs may produce electricity on demand.

<u>Intermediate conversion stage:</u> In this conversion stage, the energy converts between various energy carriers' sources, such as electricity and thermal (heating or cooling). This conversion stage is needed to balance the electricity surplus available in power grids. Coupling components represent the conversion technology that enables the Cross-Vector Sector Coupling. The conversion technologies may be bidirectional when an electrolyser is combined with fuel cells.

<u>Final conversion stage:</u> In this conversion stage, the energy converts between two energy carriers like electricity and heat (in district heating grids). The conversion process usually takes place through the end-user devices.

From an energy system integration view based on the holistic solution *LINK,* the following R&D needs emerge:

- **Design holistic architectures** for the thermal vector (heating and cooling) compatible with the holistic architecture of the energy system *LINK*. This step will create the possibility of integrating these vectors in their entirety, thus guaranteeing the scalability and repeatability of the solution.

- **Develop adequate coupling components** to realise the intermediate conversion stage**.** The latter is needed to balance the electricity surplus and, should occur at all voltage levels of the power grid. Rooftop PV systems, in particular, provide a great opportunity because they take up land that has already been developed: They do not occupy land that could be used for the production of agricultural products and the like. For example, the excess electricity from the PV systems on the roofs of buildings supplied by the district heating/cooling networks can be balanced by the P2H or P2C processes.
- **Develop customer plant management units** under the holistic approach that realise P2H and P2C, optimize all energy sources available within the plant, and provide flexibility to the grid by guaranteeing data privacy. The customer plant acts as a black box and exchanges a minimum of data with the grid, as foreseen in the holistic architecture.
- **Develop or extend real-time grid applications in all voltage levels** under the holistic approach to enable emergency- and price-driven demand response that includes, beside others, the sector coupling processes (P2H and P2C).
- **Develop appropriate market structures for all relevant vectors (e.g. electricity and thermal)** under the holistic approach to enable innovative business models and encourage investments in distributed renewable sources.

6.4. Innovative business models

- **"Smart networks":** Distributed storage systems, when intelligently connected, can form virtual smart loads for electricity grids. These are refrigerators, thermal storage and building thermal mass storage (activated building mass). For proper operation, the state of charge of the individual devices should be known and communicated to the grid management. It should be emphasized here that data privacy violations may occur; social acceptance should be investigated before any development.
- **Creation of new business models for power supply (create win-win models for production and demand sides):** Digitalisation and automation (Smart Homes, IoT etc.); Provision of a value for flexibility
- **Creation of new business models for heating and cooling as a service, benefiting from the value given to the provision of flexibility**

"Smart Networks" are enabled by advances in data availability, improved data analytics tools such as machine learning, and greater connectivity of people and devices, e.g. as part of an "Internet of Things" (IoT). Digitalization and "smart" systems can help maximize the use of renewable energy, increase energy efficiency, and provide additional flexibility in energy generation and consumption. It will also play a key role in coupling and integrating the power with the heating and cooling sectors and all sectors across the energy system.

Cross-cutting issues: Digitalisation and automation offer significant potential for new business models related to digital energy services and infrastructures. The landscape of potential applications is huge and still rapidly expanding, ranging from the use of advanced integrated simulation platforms for power generation and storage or DHC networks that follow the "digital twin" concept, over-applying machine learning for fault detection, predictive maintenance, or thermal load forecasting, to innovative block chain-based business models for smart energy contracts.

In many fields of application, developments are still in the conceptual or demonstration phase. Significant financial support is needed for the research and industrialisation of ideas. This is also important for maintaining Europe's competitiveness in global markets in digitalisation while keeping high standards for data security and data privacy. From an educational perspective, the development of digital skills will need to become a critical factor across all levels of the education system.

6.5. Public funding

Public funding plays a crucial role in the successful coupling of heating/cooling and electricity sectors in a renewable energy driven Europe. Dedicated European and national funding instruments are needed to accelerate the related technologies/systems development, reduce the burden from technical risks, and support market entry.

From the plant operator's perspective, CAPEX and/or OPEX funding (e.g. Carbon Contract for Difference [CCFD]) from European and/or national funding instruments is necessary to reduce the financial risks and to turn the business case positive. Here, existing funding instruments can be adapted (e.g. a supporting measures under the Just Transition Fund). European Regional Development Fund (ERDF) is an obvious option for eligible Member States.

Hydrogen and other long-duration energy storage benefits under EU-Catalyst partnership, funded by the Innovation Fund and Horizon Europe.

From R&D perspective further funding is expected e.g. from the Horizon Europe WP23/24 and WP25/26 to accelerate the development of the above-mentioned technologies to TRL7 (prototype demonstration in operational environment) and to ensure a fast market introduction. R&D is especially needed for system integration topics and sector coupling technologies.

That said – the bulk of funding should come from national R&I budgets.

7. POLICY AND RECOMMENDATIONS

Electricity and heating/cooling can be decarbonised nearly completely with existing technologies and resources, The transition is a development opportunity for Europe. It requires significant investment to develop, improve and deploy necessary technology at scale.

Internalising the external cost of CO_2 emissions in all sectors will be essential to facilitate the development of business models leading to carbon reduction. Similarly, flexibility must be given a value that makes it beneficial to system operators to provide it, helping to stabilise the electric grid.

Initially, financial support for the accelerated deployment of such technologies is needed and the removal of regulatory hurdles for cross-sector applications. Barriers like high levies or taxes on electricity used in storage or cross-sector applications must be removed on a national level, and a common European approach is needed to avoid market distortion.

Furthermore, clear political signal and strategy must be set up to gradually step out from subsidising and using fossil fuels in Europe's heating and cooling sectors as soon as possible. This would be a clear signal and predictable framework conditions for all the involved industries that will be prepared to deal with this drastic change.

Presently, most large power and thermal energy generation, storage and transport infrastructure suffer from complex and long permitting procedures, discouraging investors. But also, smaller scale, decentralised installations cannot be built on a harmonised administrative procedure. Using geothermal heat pumps depends on drilling permits, air source heat pumps have to comply with distancing rules and sound requirements that sometimes differ from city to city.

Next to general political support for deploying sustainable solutions, streamlining, simplification and standardisation of application procedures is needed. Since previous policy initiatives, especially outside the power sector, have not provided a broad impact, the discussion about the general pricing of CO_2 emissions is at the forefront of the political debate. It is obvious that further regulation (either through additional support of low-emission technologies or CO_2 taxation [ETS]) is needed to enable investments in low-carbon solutions. The extension of the EU ETS to cover the heat consumed in buildings should work to provide a level playing field for all heat supply technologies.

In the context of applying all the proposed methods for coupling the flexible power generation and the heating and cooling vectors, one must take into consideration two main hypothesis:

- The energy used is green, as much as possible and in accordance with ongoing EU legislation and standards, adapted for the moment of application;
- The invested carbon, specified as carbon footprint[48,49,50].

Both aspects might be used as a comparative matter addressing climate change incomprehensively. Nevertheless, not only CO_2 must be focused on, but all greenhouse gases resulted from activities, occurring during the realisation of the coupling, up to its application[51,52].

Specific challenges for RHC technologies:

Besides the general policy and regulation recommendations mentioned challenges to RHC technologies are explained in the following bullet points:

[48] https://www.britannica.com/science/carbon-footprint
[49] https://en.wikipedia.org/wiki/Carbon_footprint
[50] https://www.footprintnetwork.org/our-work/climate-change
[51] https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021
[52] https://www.iea.org/reports/global-methane-tracker-2022

- The real challenge is to set up coordinated strategies at European, national, and local levels to reduce fossil fuels to zero by 2050 including through introducing a CO_2 price signal, rebalancing of taxation on different energy carriers and the removal of fossil fuel subsidies.
- A holistic perspective on the energy system is needed taking the demand and supply needs for electricity, heating and cooling into consideration and using the advantages of the different solutions to achieve a stable energy supply.
- Beyond technological, also socio-economic challenges need to be addressed. 100% RE districts can be achieved only if innovations are not merely related to technical aspects, but also to societal changes to the development of skills, sustainable finance, market uptake measures, and citizen engagement. In decentral transition scenarios, both financial and institutional support must be provided for active end-user engagement. One-stop shops are a proven solution in this regard. In doing so, an orderly and highly cost-effective transition to a fully decarbonised H&C sector by 2050 can be ensured.
- Combination of gasification and liquefaction of any biofuels have received increasing attention, e.g. Hydrothermal liquefaction (HTL) and supercritical water gasification (SCWG) are two effective thermochemical approaches converting biomass into biofuels, and more R&I activities need to be spent to raise it to industrial levels.

RHC in industry:

- To reduce energy demand in industry, a process-by-process review of the lowest possible temperature level at which each process can operate should be performed. Temperature levels at which processes are historically operating should be questioned. Lower temperature levels allow for higher deployment shares of renewables.
- The main challenge here is related to innovative high-temperature storage, e.g. to store steam, such as Phase Change Material (PCM) or Thermo Chemical Material (TCM) storage, or even direct steam storage and underground storage can be used.
- The key challenge to achieving this will be to convince industries and private investors from a business perspective that taking concrete actions to switch to renewables and EE measures can be profitable.
- The flexibility of production poses an issue with the fluctuation of energy demand. It is challenging for the industry to plan and assess necessary adaptations and investments in the process and supply system. These challenges will increase significantly in the upcoming years.
- In the future, it will be important to support industries by developing a methodology and software tool to optimise the operation and design of industrial energy management systems. The core of this challenge is developing a holistic optimisation approach, based on (near-) accurate production data, historical data, and predicted data about the existing energy management system, both for the process demand and supply levels.

RHC in buildings:

- Enhancing stakeholder awareness: The main challenge of achieving the 2050 100% RHC target will be to inform stakeholders about the beneficial uses of RHC applications. All building owners should be engaged because tenants/renters typically will not invest in RHC for properties/buildings they do not own. A holistic approach must be adopted to overcome barriers related to the widespread acceptance using RES to supply heating and cooling.
- The main challenge is to provide cost-effective and easy/fast to install retrofitting solutions for old buildings, both for energy efficiency and heating and cooling.

RHC in districts:

- Within the regional energy system, a 100% renewable energy district enables the use of locally produced renewable energy by offering optimal flexibility, in managing consumption and providing storage capacities to the regional energy system on demand. Deploying solutions for DHC in districts with high energy density will offer efficiency gains through easier thermal storage integration, savings, risk sharing and, subsequently, increase attractiveness to commercial investors.

RHC in cities:

- The subsidiarity principle implies energy systems are operated in such a way that actions are primarily taken at the local and regional level (at the most immediate level). Only actions that cannot be properly addressed locally are handled at a wider governmental level. While this is a macro-trend for the whole energy sector, the inherently local nature of H&C supply means cities must play a leading role in developing and implementing strategies for their decarbonisation.

Provision of skills

- The energy transition towards renewable heating and cooling requires both technical, legal and economic skills[53]. While the financial and legal framework is being shaped, a lack of design, planning and installation skills emerges. Quite often the different sectors compete for the same competence. Hence a thorough assessment and EU-wide coordination effort are recommended to:
    - Ensure the education and training of a sufficient number of designers, planners and installers by making the «renewable energy» career path attractive and providing enough education and (re-) training facilities
    - On a European level, the EU Commission should provide a stock-taking of training activities taken in each member state and highlight best practices
    - The acceptance of skills should be ensured throughout the single EU market
    - A target skill level should be defined inside the EU competence system and its achievement should be observed and reported through annual EU Skills summits.

[53] REPowerEU communication: EUR-Lex - 52022DC0230 - EN - EUR-Lex (europa.eu)

8. APPENDIX

A1. Energy sources and carriers

This chapter gives an overview of the available energy sources for combined electricity/heating/cooling generation in deeply electrified integrated system. The focus will be on renewable energies, complemented by intermediate energy carriers such as hydrogen and synthetic fuels that have the potential to link different sectors. Hydrogen produced from excess renewable power generation (from solar and wind) can replace, together with sustainable biofuels, fossil fuels in the future. Existing and new CHP and cogeneration plants with renewable gases and biomass as prime movers will replace coal fired plants in the transitional phase. At the end, it is most likely that hydrogen will play a significant role replacing fossil gases in these plants for both electricity and heat supply. Fossil gases may only be used as back-up fuel in case of emergencies[54].

A1.1. Renewable sources in electricity

A1.1.1. Wind and Hydro

Wind and hydropower utilise mature technologies for the production of renewable electricity. They represent 14.7% (Wind) and 13.8% (hydro) of EU power generation (69% of renewable electricity) in 2020. The scenarios for 2030 and 2050 include an important increase of installed capacity in Europe, specifically for wind. Wind power capacity will grow at 80% by 2030 and 600% (mainly driven by offshore deployment) by 2050. In 2020, 151GW of hydro capacity was installed in the EU-27, thereof 45 GW pumped hydropower. While the potential for further capacity growth is limited concerning greenfield developments, capacity additions will come from brownfield (retrofitting non-powered dams, and modernising existing plants) and further development of pumped storage (by extension of existing schemes and new off-river pumped storage). Pumped storage expansion will provide the system flexibility needed to integrate rising VRE shares.

While hydro was traditionally the backbone for baseload generation from renewables, wind has been the key driver for the first step on the energy transition. Both will play a crucial role in the decarbonisation of power system and in the overall energy system with a highly electrified European system. While wind is focused on pure power production, hydro in addition provides system flexibility and storage capacity. Hence, both technologies are not directly applied to combined heat and power.

A1.1.2. Solar

Solar energy is energy derived from the sun. It can be used to produce electricity or heat. Solar power provides the 5.3% of EU-27 gross electricity generation (144 TWh) in 2020 3and it could achieve the 20% of demand in 2040. By the end of 2020, the EU reached 136 GW of solar PV and 2.3 GW of CSP installed generation capacity, having added more than 18 GW that year. Additionally, the current solar thermal installed capacity achieved 37.7GWth (53.9 Mm^2) and it is expected to cover at least 50% of the final energy demand for heating and cooling in Europe with solar thermal technologies (with an average collector area of 8 m^2 per European citizen). The main challenges for enhancement of the use of solar energy are reducing the generation costs and increasing efficiency and integration of converting sunlight to energy in final uses. The EU efforts on research are focused on photovoltaics (excluded from this paper), concentrated solar power and solar heating and cooling (including more efficient hybrid PV/Thermal systems and increasing the residential and industrial applications).

For the operation of solar power plants, forecast systems can provide estimates of future solar irradiation availability, ranging from a few minutes to a few days depending on the type of system. Those systems facilitate the operation and management of such power plants and, thus, its interaction with the grid, allowing to predict production fluctuations and to employ mitigation measures.

[54]"EU drafts plan to label gas and nuclear investments as green", https://www.reuters.com/markets/commodities/eu-drafts-plan-label-gas-nuclear-investments-green-2022-01-01/

A1.1.3. Geothermal

We have witnessed within the last five years (2017-2022) a resurgence of interest in geothermal power and heat, after nearly a decade of only small development in capacity in the deep geothermal sector both for electricity and for heat supply (mainly district heating).

By the end of 2020, there were 3.5 GWe of geothermal electricity capacity in Europe, distributed over 139 power plants, corresponding more than 20 TWh of geothermal electricity produced. There are also more than 200 power projects currently under development or investigation, which means that the number of plants operating in Europe could double in the near future.

In the light of the electrification of the transport sector, minerals such as Lithium and noble earth minerals are getting more and more important. First studies showed that these minerals could be extracted from geothermal brines in a sustainable way made in Europe. While supporting to cover the global demand of these materials, the production can support the economic feasibility of geothermal even in regions without optimal conditions. Other mineral such as silica, limestone and copper could be extracted from the brine.

A1.2. Renewable sources in thermal

A1.2.1. Solar thermal

Thermal energy is available everywhere. In Solar Thermal systems solar irradiation is collected and the resulting heat is transferred as a medium to a storage tank, which is always a built-in feature of solar heating and cooling systems. The heated medium can then be used i) to heat tap water, ii) for space heating, iii) in DH-networks or iv) in industrial processes. Solar thermal systems are flexible and can be used in a wide range of applications, both on a small and a large scale. Solar heat generation can be done at very different scales, from small residential systems to high scale distributed heat/cooling plants). It uses different types of solar collectors, such as flat plat, evacuate tube, high-vacuum flat-plate of concentrating collectors (parabolic trough, Fresnel) or hybrid collectors, such as Photovoltaic/thermal (PV/T) solar systems.

In Europe a total of 53 million square meters of solar thermal systems[55] is in operation, representing an estimated heat generation of 27 TWh, and a heat storage capacity of 187 GWh. Most solar thermal systems are used for domestic hot water (DHW) production. However, there is a robust increase of solar heat for industrial processes (SHIP) and solar district heating (SDH). Solar heat could cover at least 50% of the final energy demand for heating and cooling in Europe with an average collector area of 8 m2 per European Solar citizen.

A1.2.2. Geothermal

Geothermal energy has two fundamental aspects. Deep geothermal energy obtains the resource from the existence of reservoirs at comparatively high temperatures. Normally, these deposits are located at high depths, and the higher temperatures can be used to feed both district heating networks and, where appropriate, electricity production systems or even both, as Cogeneration.

There is great potential for the utilisation of geothermal energy for heating in Europe. Many locations in Europe with district heating systems can easily be adapted to make use of local geothermal resources instead of relying on fossil fuels, imported or otherwise. The substitution will increase energy security and price stability, help achieve climate neutrality as well as independence from fossil fuel sources. There is also a potential for an increased use of geothermal heat in industry and agriculture. Unlocking this potential will come through research and innovation focused on the improvement of the technology and the incorporation of geothermal energy into the energy system. In this way, geothermal energy (together with underground heat storage) will become one of the key options for the transition towards a 100% renewable heat supply in Europe.

[55] Solar Heat European Market 2019 Report - By the end of 2019.

In 2021 there were 360 geothermal district heating systems in operation, with 5.6 GWth of capacity and producing more than 20 TWh. Geothermal resource is able to cover 25% of the heat demand in the EU. More than 200 geothermal district heating (DH) projects are now under development. Leading markets such as France, Germany or the Netherlands are looking at greatly expanding the number of projects installed with more than 100 projects planned or in development. Meanwhile, all European countries are set to rapidly scale up their installed capacity, with leading emerging markets such as Poland and Denmark where geothermal is clearly identified as a strategic resource moving forward. We are also likely to see a greater diversity of temperature in geothermal resources exploited, even within a given country, as more and more geothermal reservoirs will be developed in new geographical areas and for new uses, notably for industrial processes.

Alternatively, there is shallow geothermal energy, which does not depend on the existence of high temperature resources but can in principle be used in any ground. Shallow geothermal energy is almost always associated with a heat pump, usually electric. Over 2.1 million heat pump units operating on shallow geothermal are installed, with a total capacity of 27 GWth and a production of 81.41 TWh. Geothermal energy approaches the 40 GW overall installed capacity milestone, exceeding the expectations set in 2010 by the sector.

To manage variations in supply and demand at different scales, geothermal, especially the underground thermal energy storage (UTES), provides opportunities. Thermal storage in the underground can solve this issue by transferring heat from the summer period, where it is mostly unused to the winter period. Underground thermal energy storage is applicable in different temperature ranges and has a bunch of technological solutions capable for different settings in the energy system. Only by including large scale UTES in the future energy system, the heat transition can succeed.

A1.2.3. Ambient energy

Ambient energy is available everywhere at temperatures that are varying according to geography and season. Energy is stored in air, surface water and in the ground (see previous paragraph) at comparatively low temperatures. It can be utilised by heat pumps, which transpose it to a useful level, or used directly for free cooling (this applies mainly to energy stored in water and ground. It is a viable option in a limited number of geographical regions and seasons).

In Europe about 2,17 million heat pumps were installed in 2021 (822 k air/air, 973k air/water, 128k ground or water/water and 246k sanitary hot water units).

At the end of 2021, nearly 17 million units were in operation. A split by technology reveals that the majority is using air as energy carrier (8,24 million units are of the reversible air/air type, 2,85,3 million air/water) and 1,8 million are ground coupled or of the water/water type. 1,64 million sanitary hot water and about 500k exhaust air heat pumps were in operation at the end of 2020[56]. They provided 197 TWh of useful thermal energy, 121 TWh of which being renewable energy. The installed stock of air source heat pumps avoided 30,6 Mt of CO_2 emissions to the atmosphere.

A1.3 Biomass

Currently, 90% of the energy used on the earth is gained bycombustion processes[57]. Both heat and power sectors are still dominated by combustion of fossil fuels, and the Green House Gases (GHG) generated during combustion are the main cause of climate change. Thus, the substitution of current technologies for carbon-neutral ones is one of the key priorities of EC (and ETIP-SNET and ETIP-RHC as well). However, the combustion related technologies are the backbone of our energy system, and they present several advantages for a dispatchable, stable, fast, and flexible generation of heat and power, with a very high degree of technological development level. Among others, fuels can store energy and make it available either for power or for heat generation at times when energy is needed. Hence, it is crucial to decarbonize the current combustion systems by diversification of technologies and

[56] EHPA (2021): Annual market report and statistics. The document covers the 21 major markets from the EU-27 and EFTA.
[57] T. Poinsot and D. Veynante. 2011, 3rdEdition by T. Poinsot

the substitution of current fossil by carbon-neutral fuels. The two main options are bio-based fuels and synthetic fuels.

Biomass is plant- or animal-based material used for the conversion into electricity, heat, or for the use in various industrial processes as raw material for a range of products. Biomass contains stored energy from the sun, which is absorbed by plants through the process of photosynthesis. As a storable energy carrier, biomass can significantly contribute to increasing the share of renewable energy consumption and reducing CO_2 emission from fossil fuels. Biomass is not only an energy carrier, but it is also used as food, feed, chemicals, and for biomaterials. In a bio-based economy, these different uses are linked to each other and if managed well, complementary, and sustainable.

Biomass can be collected from many sources and converted into many forms of energy. Current sources of biomass include:

- Forest products (e.g. firewood);
- By-products of the wood industry (e.g. bark, saw dust, shavings, or black liquor);
- Energy crops (e.g. rapeseed, cereals, or corn for biofuels; short rotation coppices, energy grass);
- Agricultural by-products (e.g. straw, manure, fruit wood, pruning residues);
- Biomass from waste streams (e.g. municipal waste, animal by-products);
- Aquatic biomass (e.g. microalgae).

Bioenergy is currently covering 10.5% of the gross final energy consumption in EU28, representing 59% of all renewable energy consumption (EC, 2019), and the largest share of this energy, about 75%, is used for heating. The remaining share contributes to the power and transport sectors.

Biomass covered around 87% of the total renewable heating and cooling (H&C) demand in Europe in 2016, corresponding to 17% of the total EU H&C demand[58]. 50% of the bio-heat in EU is directly used for the residential sector, 26% for industrial processes, 16% is derived heat (heat only and combined heat and power (CHP) plants), and the remaining 8% is used in services and other residual sectors. The development of new technologies will enable the production of secure and sustainable biomass supplies, clean and effective conversion processes, high-quality fuels, and optimally integrated solutions for households, services, industry, and district heating and cooling (DHC).

In 2018, the European citizens generated around 220 million tonnes of municipal solid waste (almost 500 kg per citizen). Half of this number was made of non-recyclable waste, which can be treated by Waste-to-Energy or landfilled. Biomass materials accounted for about 61% of the weight of the combustible MSW and for about 45% of the electricity generated[59]. Hence, another important challenge is correlated with the increase of circularity of waste as source of energy and materials.

A1.4 Hydrogen and synthetic fuels

Green synthetic fuels are energy carriers, a way to store electricity from RES in form of chemical energy using different chemical reactions. They enable long-term storage, distribution, and transport. Green hydrogen[60] is generated by means of the separation of hydrogen and oxygen from water by means of electrochemical reactions (electrolysis or photo-electrolysis) or by thermochemical processes (thermolysis and thermochemical processes based on CSP). While electrolysis technology is most developed, today's production volume of renewable hydrogen is still insignificant. Current hydrogen production in Europe is close to 10 Mt/y with 95% being produced from fossil fuels. It is expected that the production of hydrogen produced only with renewable energies will significantly increase in the future, however the speed of development mainly depends on political decisions.

[58] EUROSTAT, 2017
[59] ttps://www.eia.gov/energyexplained/biomass/waste-to-energy.php
[60] Only "Green hydrogen" is considered in the 2050 scenario and covered in this work. Green hydrogen is referred to 100% RES-based production of hydrogen, in contrast to "grey hydrogen" (the main current system based on fossil fuels reforming technologies) and "blue hydrogen" (integrating carbon capture technologies with grey hydrogen).

The Green Deal identifies the relevance of clean (green) hydrogen for achieving carbon neutrality by 2050, to be used predominantly in those hard to abate sectors where no or costly direct electrification options exist. While hydrogen can be used in multiple end use (heat and power) sectors (see Fig. 10) transport and storage are challenges that warrant a cautionary approach on where and when to use it. The EU objectives (from REPowerEU plan) aim at the installation of at least 17.5 GW of renewable hydrogen electrolysers by 2025 with a production of 1 Mt/y, during this phase. In a second phase (2025 to 2030) hydrogen should be part of an integrated energy system with a strategic objective to install at least 40 GW electrolyser capacity and an annual production volume of up to 10 Mton the EU of domestic renewable hydrogen production and 10 million tonnes of renewable hydrogen import. In a third phase, from 2030 onwards and towards 2050, renewable hydrogen technologies should reach maturity and be deployed at large scale to reach all hard-to-decarbonise sectors where other alternatives might not be feasible or have higher costs[61].

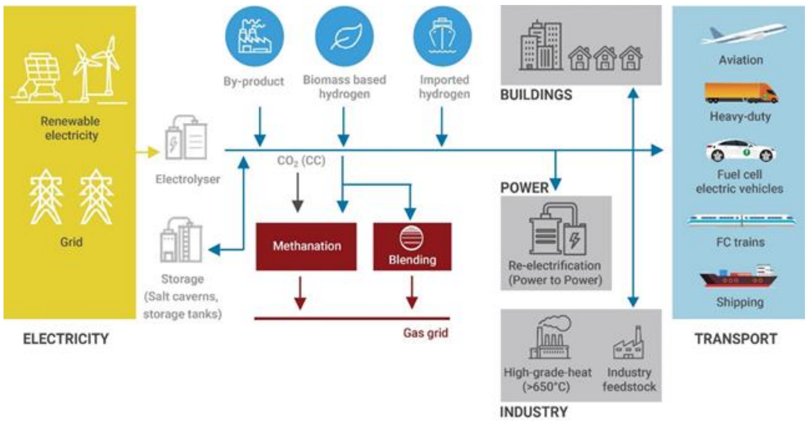


Figure 10: Integration of vRES into end uses by means of hydrogen[62]

JRC forecast estimate that the green energy potential is abundant in most European regions to cover total electricity demand & electrolysis' requirements for H_2. The conversion of current fossil-based hydrogen production would require 290 TWh of electricity (about 10% of current RES electrical production). However, the potential for hydrogen production in 2050 is enormous achieving up to 2,250 TWh and 5,250 TWh at European and global levels[63].

Moreover, hydrogen is the basis for the production of other synthetic carbon-neutral fuels that can be used in current systems with minimum technological modifications, in multiple applications such as space, energy, transportation, and aviation. There are under development multiple production routes of these fuels, that also requires a renewable source of carbon (biomass or direct CO_2 from air) to produce gaseous fuels (mainly Synthetic Natural Gas, P2G)[64] or liquid fuels (BtL, PBtL, and PtL routes)[65]. Finally, the production of ammonia from RES is gaining more interest as a fuelling vector[66].

[61] EC 2020, A hydrogen strategy for a climate-neutral Europe COM/2020/301 final https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0301
[62] IRENA (2018), Hydrogen from renewable power: Technology outlook for the energy transition, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/energytransition/Power-Sector-Transformation/Hydrogen-from-Renewable-Power
[63] G. Kakoulaki, et al., Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables, Energy Conversion and Management, Volume 228, 2021, 113649, https://doi.org/10.1016/j.enconman.2020.113649].
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[65] Pregger, T., et al., Future Fuels—Analyses of the Future Prospects of Renewable Synthetic Fuels. Energies 2020, 13, 138. https://doi.org/10.3390/en13010138
[66]A. Valera-Medina, et al.,Review on Ammonia as a Potential Fuel: From Synthesis to Economics, Energy & Fuels 2021 35 (9), 6964-7029 https://doi.org/10.1021/acs.energyfuels.0c03685

A1.5 Waste heat recovery (Low, medium temperature source)

A1.5.1 Waste heat from other processes and infrastructure

Energy at a low temperature level can be extracted from building structures, such as foundations and the buildings (concrete) core. Likewise, from infrastructure installations such as road and rail/subway tunnels, sewage systems etc. This energy can be upgraded by the means of heat pumps to a useful level.

With many office buildings and data centres being air-conditioned year around, the use of excess heat from cooling should always be considered. It can be used on-site for hot water and heat production or fed into low-exergy energy grids.

A1.5.2 Industrial heat

The energy conversion from primary sources to final use are subjected to several losses mainly due to two steps: 1) primary energy carrier conversion (i.e. electricity generation, heat production and petroleum refining), or 2) end use conversion (i.e. industrial processes, commercial and residential activities, transportation). The major losses can be identified in general as waste heat and industrial processes presents the higher potential to valorise the waste heat as power[67].

The industrial sector accounted for 25.7% of total European final energy use (in 2020)[68] and 24% of Global emissions in 2018[69] (20% in Europe).. Energy represents up to 20% of the total production costs for energy intensive industries in Europe[70], and a significant amount of its energy (between 20 and 50%) is lost in the form of waste heat (i.e. as hot exhaust gases, cooling water, and heat losses from equipment and products)[71]. Enormous efforts have been carried out to recover this valuable resource internally in industrial processes or externally after intermediate transformation processes. Industrial waste heat recovery potential is still unlocked due to several technical and non-technical barriers.

The potential of waste heat energy in industry in EU27+UK is estimated between 304 and 918 TWh/y[72,73,74.] However, the final use of the energy also depends on the waste heat temperature. Thus, only one third of the energy can be potentially converted into mechanical work (according to Carnot's theorem). Hence, theoretically by means of the waste heat conversion to power it could be possible to cover between 11% and 32% of industrial and 4% and 11% of global EU electrical consumption (which were 934 TWh and 2778 TWh respectively in 2020).

Industrial heat available depends on the industrial sector. The main potential is observed in Iron and Steel industries, where the amount of heat and range of temperatures present the higher potential. The other sectors with high potential are Non-metallic mineral, Non-ferrous metal, and Chemical and Petrochemical sectors (Fig. 11).

[67] C. Forman, et al., Estimating the global waste heat potential, Renewable and Sustainable Energy Reviews, Volume 57, 2016, Pages 1568-1579, https://doi.org/10.1016/j.rser.2015.12.192]
[68] Eurostat. Energy Data 2020. Doi: 10.2785/68334
[69] IEA (2020), Tracking Industry 2020, IEA, Paris https://www.iea.org/reports/tracking-industry-2020
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[71] A.SPIRE(2016), Spire Roadmap 2030, SPIRE, Brussels, https://www.spire2030.eu/sites/default/files/pressoffice/spire-roadmap.pdf
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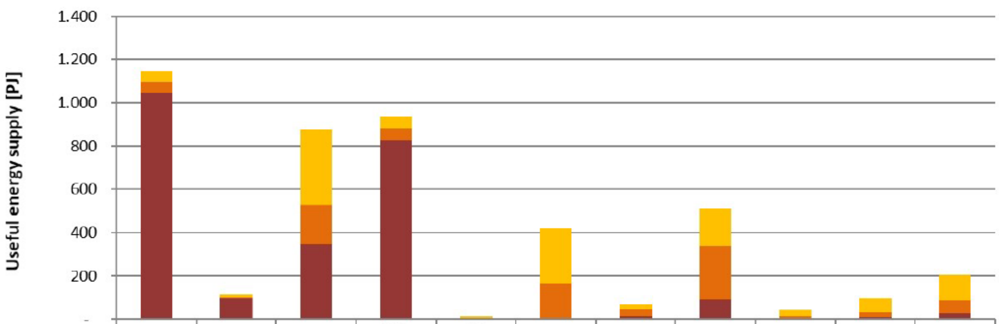
[73] L. Miró, S. Brückner, L. F. Cabeza, Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries, Renewable and Sustainable Energy Reviews, Volume 51, 2015, Pages 847-855, https://doi.org/10.1016/j.rser.2015.06.035
[74] Bianchi, G., et al. Estimating the waste heat recovery in the European Union Industry. Energ. Ecol. Environ. 4, 211–221 (2019). https://doi.org/10.1007/s40974-019-00132-7



	Iron & Steel	Non-ferrous metal	Chemical	Non-metallic mineral products	Ore extraction (except fuels)	Food, drink & tobacco	Textile, leather & clothing	Paper & printing	Transport Equipment	Machinery	Other Industries
Low Temp < 100 °C	50	10	351	58	7	256	23	175	29	67	119
Med Temp 100 - 400 °C	53	5	180	54	5	162	36	246	10	22	58
High Temp > 400°C	1.045	98	346	827	-	-	13	91	4	10	29

Figure 11: Waste heat potential per industrial sector[75]

A2. Heat Pump Potential

The capacity of available technology ranges from a few Kilowatts to several Megawatts. Cascading deployment is possible. Up to date, industrial heat pumps can deliver heat to a maximum temperature of 160°C Currently several research groups and OEMs are working to develop industrial heat pumps that can deliver heat at temperatures up to 250°C and thus cover a large portion of the industrial heat demand. Once heat pumps for temperatures up to 200 °C become available, the technology has the potential to deliver 37% of the industrial process heat and thus save approximately 146 Mt/a of CO_2 emissions from this sector. This number becomes even higher if the technology reaches 250°C.

A3. Innovative waste recovery cycles

ORC-Cycles: The Rankine cycles are the basis of thermal power generation, using water as working fluid in high temperature applications and large centralised systems. The use of organic fluids allows smaller capacities and lower operating temperatures. Organic Rankine Cycle (ORC) uses an organic, high molecular mass fluid with a liquid-vapour phase change at a lower temperature than the water-steam system, usually between 100°C and 300 °C. The use of organic working fluids allows to work at small and medium scale power plants. The ORC presents a lower performance and higher levelised cost of energy than Rankine cycles but it allows to valorise smaller heat sources at lower temperatures than classical thermal power plants. ORC systems are therefore technically suitable for the conversion of renewable or renewable-equivalent energy sources[76]. At the end of 2020, the cumulated ORC installed capacity was 4.07 GW. Since 2016, the overall ORC market increased by 40 % (+1.18 GW) in terms of installed capacity and by 46 % (+851) in terms of installed plants. Regarding the capacity increase between 2016 and 2020, the largest increase is due to geothermal application (+970 MW, +45 %), while waste heat systems have the largest growth concerning the number of installed systems (628 plants, + 207 %)[77].

Kalina cycles: The Kalina cycle is principally a “modified” Rankine cycle, using an ammonia–water mixture as the working fluid. The applications of this cycle are focused on geothermal and industrial waste heat recovery.[78]

Trilateral Flash Cycle (TFC): Trilateral Flash Cycle is a bottoming thermodynamic cycle particularly suitable for waste heat sources at temperatures below 100 °C. Hence the potential of application at European industry

[75] Elena Guillen-Burrieza, «Project Deliverable 8.2: Assessment of socio-economic impact scenarios of SHIP development in the EU,» INSHIP (H2020), 2017
[76] B.F. Tchanche, et al., Low-grade heat conversion into power using organic Rankine cycles – A review of various applications, Renewable and Sustainable Energy Reviews, Volume 15, Issue 8, 2011, Pages 3963-3979, https://doi.org/10.1016/j.rser.2011.07.024
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469 TWh[79]. TFC can be considered a modified ORC characterized by a two-phase expansion process in order to involve a two-phase heat recovery.

sCO_2-cycle: The supercritical CO_2 (sCO_2) Brayton cycle has recently been gaining a lot of attention for application to power generation from renewable and industrial heat recovery. The advantages of the sCO_2 cycle are high efficiency in the mild turbine inlet temperature region and a small physical footprint with a simple layout, compact turbomachinery, and heat exchangers[80]. This technology can be applied in plant size similar to MW ORC, but using a heat source compatible with ORC and steam cycles (250-600°C).

The working fluid is carbon dioxide in supercritical conditions, i.e. above the critical point (31°C and 73,8 bar). Under these conditions it adopts properties midway between a gas and a liquid. It expands in its container like a gas but with a density like that of a liquid. Such conditions can be profitable to increase the power conversion performance due to a high energy density compared to other working fluids. Moreover, it is benign (non-explosive, non-flammable, non-corrosive and non-toxic), thermally stable, and relatively inexpensive.

Multiple configurations are proposed as function of the heat source and integration level[81]. This technology is currently under demonstration at industrial level (TRL 7-8) in an H2020 project called CO2OLHEAT using the waste heat from a cement plant as heat source to produce power at MWe scale[82].

A4. Cogeneration – facts and figures

The supply of high-temperature heat first drives a gas or steam turbine-powered generator. The resulting low-temperature waste heat is then used for water or space heating. At smaller scales (typically below 1 MW), a gas engine or diesel engine may be used. Cogeneration plants have been one of the first applications for “sector coupling”, combining supply of electricity and heating/cooling for industrial or residential purposes, i.e. connecting different sectors.

Table 2: Typical performances of co-generation plants.

Technology	Main process/devices	Max. electric efficiency level today	Useable heat @ high electric efficiency *)	Resulting Fuel efficiency
Fuel Cells	Fuel Cell, heat recovery system	60%	25%	85%
Thermal plant	Boiler/steam turbine/condenser	45%	41%	86%
Gas engine	Internal combustion engine, heat recovery system	48%	39%	87%
Combined cycle plant	Gas turbine/ heat recovery steam generator/steam turbine / condenser	63%	28%	91%

***(75% of waste heat assumed to be used (for all thermal processes, less for fuel cell)**

[79] G. Bianchi,et al., Development and analysis of a packaged Trilateral Flash Cycle system for low grade heat to power conversion applications, Thermal Science and Engineering Progress, Volume 4, 2017,Pages 113-121, https://doi.org/10.1016/j.tsep.2017.09.009
[80] Y. Ahn, et al. Review of supercritical CO2 power cycle technology and current status of research and development, Nuclear Engineering and Technology, Volume 47, Issue 6, 2015, Pages 647-661, https://doi.org/10.1016/j.net.2015.06.009
[81] F. Crespi, et al. Supercritical carbon dioxide cycles for power generation: A review, Applied Energy, Volume 195, 2017, Pages 152-183, https://doi.org/10.1016/j.apenergy.2017.02.048
[82] https://co2olheat-h2020.eu/

A5. Shallow geothermal short/medium/seasonal energy storage

1st Example (short term storage): simultaneous production of heat and cold in a local DHC. The heat pump produces a high efficiency heat flow into the ground from a building requiring cooling. A simultaneous process requiring heating could benefit from the rising temperature in the ground, partially reusing the heat, if the heat pumps are coupled to the same ground-heat exchanger.

2nd Example (medium term/seasonal storage): the same building uses heating and cooling depending on the season or condition. The ground heat exchanger is designed to allow a balance of heat/cold into the ground that ensures that underground temperatures are undisturbed in the long term. This strategy maximizes the heat pump efficiency and thus stabilizes the demand for electricity.

3rd Example (seasonal storage): By means of seasonal storages (Tank Thermal Energy Storage – TTES, Pit Thermal Energy Storage – PTES, Borehole Thermal Energy Storage – BTES and Aquifer Thermal Storage - ATES), heat/cold is transferred via a heat pump in such a way that in summer the heat extracted from the building is stored in one part of an aquifer (hot aquifer), whilst in the winter the heat is extracted from another part of the same aquifer or a different one. This results in two regions acting as cold/heat reservoirs are created as a result of system operation which as a consequence lead to a drastic reduction of electricity consumption.

Seasonal storages may also be heated via thermal RES technologies, such as solar thermal or biomass, and used as cold source for heat pumps in the heating season.

There are many more options, but these three examples are just an illustration on how geothermal energy can be used in a variety of ways to store heat/cold either daily or seasonally thus allowing for a more efficient and rational use of its intrinsic thermoelectric sector integration.

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