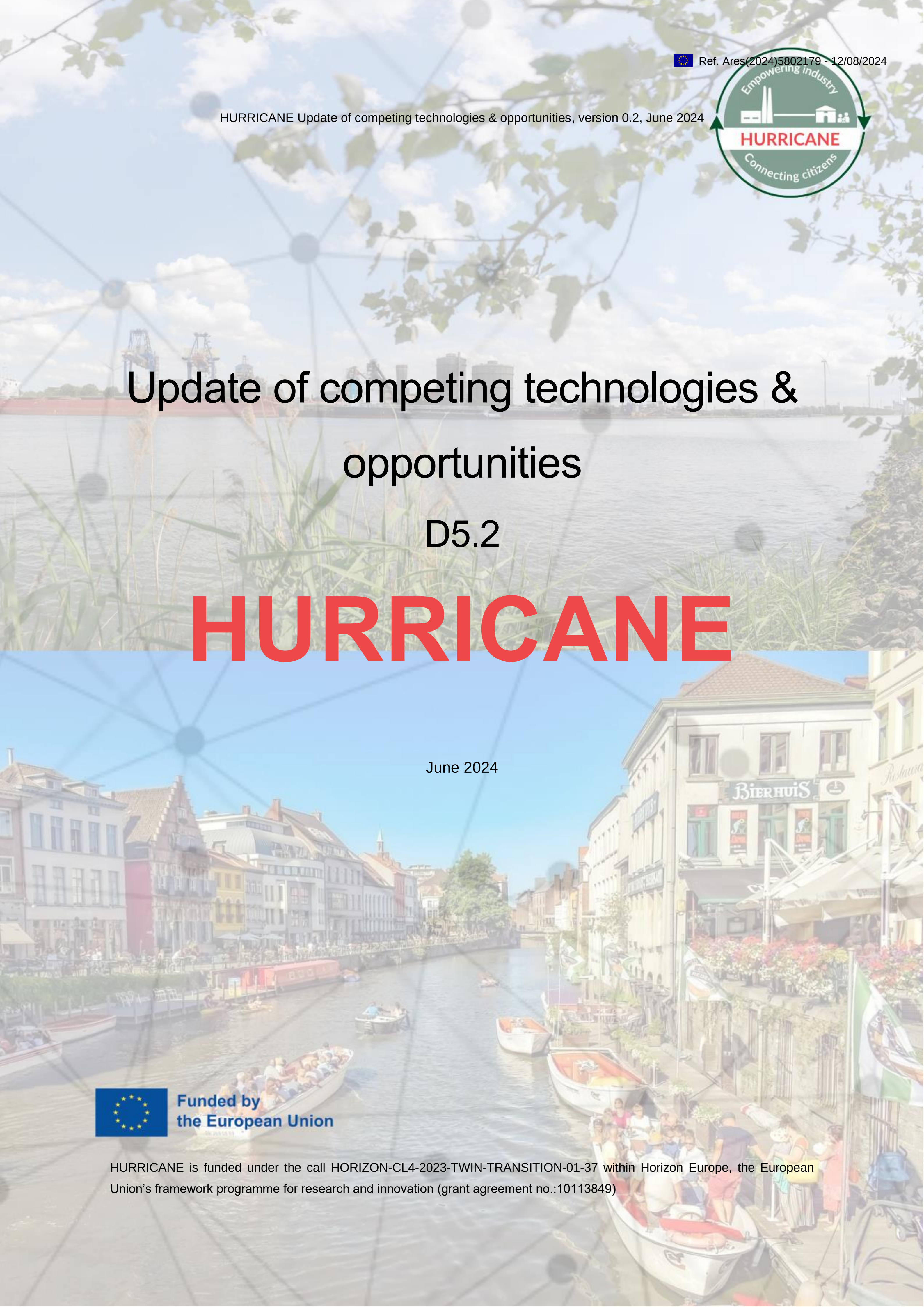

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Update of competing technologies & opportunities

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HURRICANE

June 2024

Funded by the European Union

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Project Summary

Within HURRICANE a sector-coupling circular hub centred around the ArcelorMittal Ghent site will be created. We will target efficient resource management together with the recovery and utilization of squandered industrial waste heat and water. Together with ArcelorMittal Ghent's ongoing initiatives, this will lead to a reduction of energy, water and raw materials by at least 20%. Thanks to the ongoing projects taking place within and around the Ghent site, the site is already well connected to many other industries like waste suppliers, chemical producers (ethanol offtake & H2 waste gas), renewable power producers, and wastewater treatment. It has become a multi-sectoral hub leading to efficient implementation of industrial symbiosis concepts. The Ghent site has a significant amount of recyclable energy, material and water that allows this symbiosis. These aspects are not only from the steel making processes, but also from other operations taking place in the mentioned "multi-sectoral" hub. This hub can be further enhanced with the integration of waste heat with its ongoing initiatives. Our solution aims at developing and demonstrating novel heat recovery (heat exchanger) and upgrading (heat pumps) solutions from selected operations and then coupling it with the internal and external off takers by means of a heat grid. With digital tools, aspects like broadening the district heating network, and adapting the heat demand profile of the buildings to better match the intermittent of the waste heat, can be optimized. Finally, an integrated software tool for circular hubs that combines the different tools and data produced at the different operations will be developed and validated. Through two virtual demonstrations and circular hubs blueprint the replication potential will be proven. The consortium is formed by 12 partners from 5 different countries, including 4 research organizations, 1 large End User, 3 SMEs, 3 civil organizations and 1 linked 3rd party.

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List of abbreviations

- CFD: Computational Fluid Dynamics
- CHP: Combined Heat & Power
- CSP: Concentrated Solar Power
- DHC: District Heating and Cooling systems
- GDPR: General Data Protection Regulation
- ORC: Organic Rankine Cycle
- PCMs: Phase Change Materials
- RES: Renewable Energy Sources
- TEG: Thermoelectric Generators
- TES: Thermal Energy Storage

1 Executive Summary

This document reports on the current competing technologies and opportunities related to heat recuperation, heat storage (thermal batteries), heat distribution (heat grid) and the possibilities to convert waste heat to electricity, thermoelectric generators and Organic Rankine Cycles), to use waste heat directly in other process steps or to use it for district heating.

In the operations of a steel mill, such as during hot rolling processes, significant amounts of waste heat are generated, presenting both challenges and opportunities for enhancing energy efficiency and sustainability within the industry. Competing technologies and opportunities abound across various aspects of heat management within a hot rolling mill setting. These include heat recuperation, where conventional methods involving cooling water or air are being increasingly supplemented or replaced by advanced heat exchanger designs like double tube, shell and tube, tube in tube, and plate heat exchangers. Innovative heat exchanger designs, often optimized through Computational Fluid Dynamics (CFD) simulations and/or heat transfer models, play a crucial role. These innovations aim to capture waste heat more effectively, not only from cooling processes but also from heat radiation emitted by hot steel products like steel coils.

Additionally, there are new opportunities to store heat or energy, especially with thermal energy storages. These systems can be based on sensible, latent or chemical storage technologies to store excess heat during peak production times for later use, thereby improving energy efficiency and reducing operational costs. Additionally, efficient heat distribution within a steel mill can be achieved through the implementation of heat grids. These grids facilitate the distribution of recovered waste heat to various industrial processes within the steel mill or even to external off-takers, enhancing efficiency and flexibility through integration with smart controls and monitoring systems.

Furthermore, various technologies exist for converting waste heat into electricity, offering additional avenues for energy optimization. Thermoelectric generators for example, convert waste heat directly into electricity, thus improving overall energy efficiency. Electrolysers use electricity, produced by waste heat, for hydrogen production, contributing to the decarbonization efforts of the steel industry. Additionally, industrial heat pumps can utilize waste heat to meet both heating and cooling needs, further optimizing energy usage within the steel mill.

Incorporating these competing technologies and opportunities for heat recuperation, storage, distribution, and electricity generation holds immense potential for enhancing the sustainability and efficiency of hot rolling mills within steel mills. Continued research, development, and implementation of these innovative solutions are essential for driving progress towards a more sustainable future for the steel industry.

2 Introduction

The latest advancements in energy recuperation within the hot strip mill industry involve innovative technologies aimed at boosting efficiency, reducing environmental impact, and enhancing operational performance. For instance, waste heat recovery systems are being refined to capture and convert waste heat into usable energy, cutting energy demand and operational costs. Similarly, thermal energy storage systems are integrated into hot strip mills, storing excess heat generated during peak production periods for use during higher demand intervals, optimizing energy efficiency. Advanced heat exchanger designs, characterized by optimized and enhanced surface area configurations and optimized fluid dynamics, are revolutionizing heat transfer concepts, further pushing energy recuperation efforts. Furthermore, state-of-the-art control and monitoring systems, leveraging real-time data analytics and machine learning algorithms, are revolutionizing energy recuperation processes, identifying opportunities for energy savings and minimizing energy losses throughout mill operations. These new ideas are leading the way in making hot strip mills more sustainable and efficient.

2.1 Scope of this deliverable

In the steel production industry, saving energy and reducing carbon emissions are crucial steps towards achieving CO_2 neutrality. This deliverable explores some advanced technologies and opportunities for waste heat recuperation and energy savings within hot strip mills. The deliverable reviews the latest advancements and best practices related to these technologies. It focuses on innovations in heat grids, exotic heat exchangers, thermal energy storage, thermoelectric generators, high-temperature heat pumps, and electrolysers. These technologies enhance energy efficiency and reduce the environmental impact of the hot strip mills. The scope is to provides a thorough understanding of these technologies and their potential to save energy, reduce pollution, and promote a sustainable future for the steel industry.

2.2 Outline of this deliverable

In industries like steel production, saving energy and reducing carbon emissions are becoming top priority to become CO_2 neutral. Technologies like energy recuperation in hot rolling mills help achieve this by making processes more efficient and reducing environmental impact. The following topics focus on the latest technologies and opportunities in the field of waste heat recuperation and energy savings that could potentially be implemented in a hot strip mill:

- Heat grids: heat grids are networks that distribute heat efficiently across different areas, using renewable energy and waste heat. They help create a more sustainable energy system for industries, buildings and homes.
- Thermal energy storage: thermal energy storage systems store energy when it's not needed to be used later, balancing energy supply and demand.
- Thermoelectric generators: thermoelectric generators convert heat into electricity, offering a clean way to generate power from waste heat and other sources.
- High temperature heat pumps: high-temperature heat pumps provide efficient heating by increasing the temperature level of lower temperature renewable or waste heat, reducing emissions, and saving energy in various industries.
- Electrolyzers: electrolyzers are devices that produce hydrogen, a clean energy source when using renewable energy. This hydrogen can be used in fuel cells, energy storage, and industry, helping to cut carbon emissions.
- The Organic Rankine Cycle (ORC) is a thermodynamic process based on the Rankine cycle that converts waste heat to electricity and heat at lower temperatures: Instead of water, another organic process medium with a low evaporation temperature is used for the Rankine cycle.

Overall, these technologies help industries save energy, reduce pollution, and move towards a cleaner, more sustainable future.

3 Latest technologies and opportunities in the field of waste heat recuperation and energy savings

3.1 District heating networks and solutions

Working principle

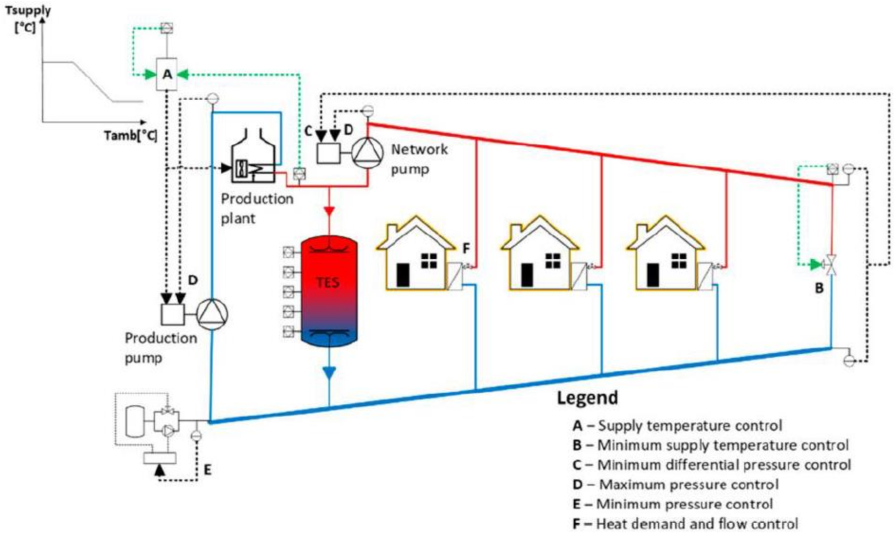
District heating systems are centralized networks designed to efficiently distribute heat from centralized plants to multiple buildings or facilities within a local area. The process begins with heat generation at centralized plants using various energy sources like natural gas, biomass, or waste heat. This heat is then transported through a network of pipes (supply pipes) to individual buildings, where it is transferred to the internal heating systems. After releasing heat to the buildings, the cooled fluid returns to the central plant through a separate network of pipes (return pipes). District heating networks can also be operated with multiple heat sources at different geographic locations.

District heating networks can furthermore be categorized in what is called generation of networks. Most used today are the 3rd generation district heating networks based on pressurised water as the heat carrier and supply temperatures often below 100°C. The 4rd generation types provides the heat supply of low-energy buildings with low grid losses. The use of low temperature heat sources is used in combination with the operation of a smart energy system. Recently, 5th generation district heating and cooling network were identified and are characterised by even a low(er) temperature supply, bi-directional operation (providing heating and cooling simultaneously), decentralised energy flows (by means of multiple heat sources and heat sinks in the network), and heat sharing (recovering waste heat and share it with different users) (.

Several demonstration projects have shown that district heating networks can play a central role in our future energy system by offering flexibility and by enabling a high integration of Renewable Energy Sources (RES). By using advanced control technologies, supply and demand optimisations can be achieved increasing the system efficiency and maximizes the use of renewable energy. District heating maximizes energy efficiency by utilizing waste heat and integrating renewable energy sources like solar or geothermal energy. Overall, district heating networks offer a cost-effective and eco-friendly solution for heating communities, optimizing energy use, and reducing greenhouse gas emissions.

Current best Practices

Traditionally, district heating networks are centrally operated (and at substation level) without advanced control methodologies, often operated with a high share of fossil fuel (figure 1). This operation's focus is to ensure a sufficient supply temperature and optimize the system's economic performance. In classical district heating networks, the supply and return temperature, minimum differential pressure, maximum pressure, minimum pressure, and the heat demand and flow are controlled and monitored. Traditional systems focus on keeping the pressure high in the network, satisfying the energy demand of the customers and actions towards keeping customers connected to the network so that they do not chose another heating installation when renovating their buildings. To incorporate a higher share of renewable and excess heat (both unpredictable) in district heating networks, advanced control algorithms are needed. The traditional way of controlling district heating networks is moving for a centralised control to a more advanced control system incorporating different types of smart meters, data, etc.



Source: Buffa et. al. 2021.

Figure 1: Traditional control of district heating networks (Source: Buffa et al. 2021).

Digitalization, data collection and technological innovations in smart meters, advanced sensors, etc. have made it possible to go beyond the state of the art by making use of the large amount of data that is available. Furthermore, by using and combining in an optimal way sensor and smart meter data, weather data, building data, data from other sources solutions, it is possible to control the energy demand of the individual connected buildings, the temperatures and flows of the network, enabling a higher integration of RES in DHC (District Heating and Cooling) systems.

DHC systems will need to be intelligent and flexible to manage multiple generation sources, and enable the integration of RES, as well as excess heat from industries, supermarkets, and data centres. By implementing an advanced control of the energy demand, lower system temperatures and smoother hydraulic operation of the network will be the result.

Latest advancements

The upcome of digitalisation in several sectors and in different areas of competences (energy, water, climate, etc.), the use of big data and cloud technology in general, have made it easier to cost-effectively optimise district heating network operations. Technical equipment such as smart heat meters, digital thermostats and thermostatic valves, and digital sensors have become much more intelligent and less expensive, enabling higher granularity of monitoring capabilities and control and provide a large volume of data.

District heating networks operators will be able to receive/collect an abundance of data on their customers' heat consumption, temperature levels, etc. Today, most operators are even not aware of how to use, process and exploit the data in their daily operation. For this, tools, methods, and resources are needed to discover the potential of this data and to convert the data to knowledge. This can improve the operational aspects by providing their customers with more detailed information and insights on their energy consumption or to operate the network more efficiently. Besides this, the large amount of data also brings additional risks to the utility's operations such as cybersecurity and legislation aspects such as GDPR (General Data Protection Regulation).

Furthermore, the uptake of artificial intelligence has opened the way to optimise the thermal network based on real-time information, simulation and forecasting models that can learn and predict the behaviour. These so-called self-learning control algorithms can optimize the behaviour of the network during the operation. Intelligent control of district heating networks is a prerequisite for an effective lowering of the temperature in DHC system with multiple generation sources and with a fluctuating energy supply and demand. In the literature, multiple references can be found to advanced control methods such as model predictive control, mixed integer linear programming and multi-agent systems, which all have proven to be effective in reducing operational cost, energy consumption and efficiency and peak loads.

Forecasting algorithms can predict the heat consumption of a network based on historical data, weather forecasting, building characteristics, indoor climate conditions, etc. Using this forecasted energy demand, the utilities can match this with an energy supply at the lowest operational cost or with the highest share of renewable energy. Another example is the lowering of the peak heat load in district heating networks by using the thermal mass of the building. District heating networks suffer from high peak demand leading to inflated operational costs. High supply and return temperatures in the distribution network can cause up to 20% of the heat to be lost.

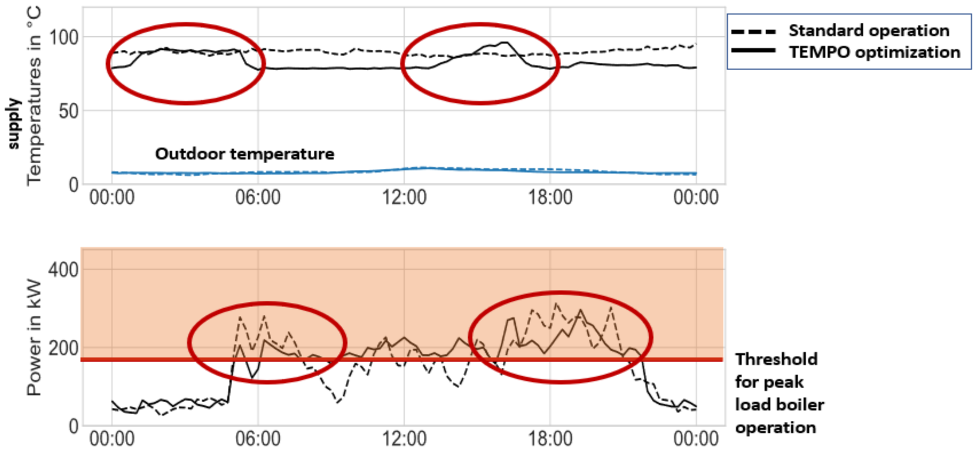


Figure 2: Peak load reduction by advanced control systems (Source: H2020 TEMPO project)

Several EU projects have developed, tested, and evaluated real-time solutions for smart and intelligent control of district heating networks. The H2020 STORM project developed, implemented, and tested a market-ready product in 2 demonstration projects in Sweden and the Netherlands, reducing the peak load in the network up to 20%. Another example is the Horizon 2020 project FLEXYNETS, a project integrating multiple generation sources by managing energy at different temperature levels and assuring optimized exergy exploitation.

The market of advanced control systems in district heating networks is still limited across the EU. Most business models and district heating utilities exploiting these technologies are found in the Nordic and Benelux countries.

European projects

- **H2020 Reuseheat project**. The project showcased replicable models enabling the recovery and reuse of excess heat available at urban level, with the aim to increase energy efficiency of district heating and cooling systems in cities across Europe. The project focused on: integrating low-carbon sources in heat networks, making use of heat that would otherwise go to waste and boosting energy efficiency in cities. Link to more information: https://www.euroheat.org/dhc/eu-projects/re-use-heat

- **H2020 Rewardhea**t. REWARDHeat will promote punctual metering, thermal storage management, and smart network control as means to enable and optimize the exploitation of renewable and excess heat in DHC networks. At the same time, this approach permits a change of paradigm concerning the business models devised: thermal energy will be sold as a service to the customers, rather than being viewed as a commodity. Solutions will be developed at 8 demonstration sites across 7 European countries. Additionally, 3 early adopters not implementing actual demonstration measures, but fully involved in the project consortium, will develop preliminary projects for the upgrade of their networks integrating excess heat from different sources. Link to more information: https://www.rewardheat.eu/en/ .

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3.2 Heat absorbing panels by infrared radiation

Working principle

Heat absorbing panels designed to capture infrared radiation function by utilizing specialized materials that efficiently absorb the infrared wavelengths emitted by hot surfaces of products. These panels convert the captured radiation into thermal energy, which can then be used for various applications such as preheating or process heating by means of a heat exchanger. The principle involves selecting materials with high emissivity and low reflectivity for infrared radiation, ensuring maximum absorption and minimal energy loss.

In contrast, solar boilers operate on the principle of converting sunlight into thermal energy. They typically use solar collectors, which absorb sunlight and convert it into heat, transferring this heat to water or another fluid for use in heating applications. Solar boilers are effective in environments with ample sunlight and are widely used in residential and commercial buildings for hot water heating and space heating purposes. Comparatively, heat absorbing panels by infrared radiation offer distinct advantages in specific industrial contexts where direct exposure to high-temperature surfaces of products occurs. They are particularly suitable for capturing infrared radiation from processes like steel manufacturing or glass production, where waste heat recovery is crucial. In contrast, solar boilers excel in applications where direct sunlight is abundant and consistent, such as in residential solar water heating systems or solar thermal power plants.

Both technologies contribute to renewable energy strategies by utilizing natural energy sources—solar radiation in the case of solar boilers and infrared radiation in the case of heat absorbing panels. Each technology's effectiveness depends on environmental factors such as sunlight availability or the presence of infrared-emitting sources, highlighting their complementary roles in enhancing energy efficiency and sustainability across different sectors of industry and residential energy use.

Latest advancements

Recent advancements in heat absorbing panels for capturing infrared radiation from hot products have significantly improved efficiency and durability. One key aspect in radiative heat transfer enhancement, utilizing selective coatings (i.e. multilayer thin films, nanostructured materials, hybrid organic-inorganic compositions, high-temperature stable ceramics) to optimize the absorption and conversion of infrared radiation into thermal energy. Another major advancement is the development of selective absorbers, engineered materials that efficiently capture specific wavelengths of infrared radiation while minimizing reflection and thermal losses, making them ideal for high-temperature applications.

Current best Practices

Current best practices for heat-absorbing panels by infrared radiation from hot products focus on enhancing efficiency, durability, and integration with other energy systems. In the steel making industry, a lot of its waste heat from the products is released in the air. Capturing and reusing this heat can significantly reduce energy consumption and carbon emissions. To maximize the efficiency of heat-absorbing panels, advanced selective absorbers are employed to enhance the radiative heat transfer. Selective absorbers are designed to absorb specific wavelengths of infrared radiation while minimizing reflection and thermal losses. The selective coatings and material (i.e. aluminium) are crucial in applications where maximizing heat absorption is essential. For instance, in solar thermal power plants, selective absorbers are used in panels to capture and convert sunlight into thermal energy with high efficiency. This technology can also be applied in industrial settings, where heat from hot products can be captured more effectively, reducing the overall energy consumption.

Coupling heat-absorbing panels with thermal energy storage systems significantly enhances their effectiveness. For example, Phase Change Materials (PCMs) can store large amounts of thermal energy and release it when needed. In a hot strip mill, excess heat captured by infrared panels during peak production periods can be stored in PCMs. This stored energy can then be used during off-peak times, ensuring a steady and efficient energy supply. Another example is using thermochemical storage systems that store energy through reversible chemical reactions, which can be particularly useful in industries requiring long-term and high-capacity energy storage. The durability of heat-absorbing panels is important, especially in harsh industrial environments. Materials and coatings used in these panels must withstand high temperatures and corrosive conditions.

Implementing sophisticated control and monitoring systems could optimize the performance of heat-absorbing panels. These systems could utilize real-time data analytics, machine learning algorithms, and predictive modelling to adjust operational parameters dynamically. For example, in a manufacturing plant, sensors can monitor the temperature and heat flux of panels and automatically adjust their position or surface properties to maximize heat capture. Predictive maintenance can also be scheduled based on data trends, preventing unexpected failures, and optimizing energy efficiency.

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3.3 Thermal energy storage

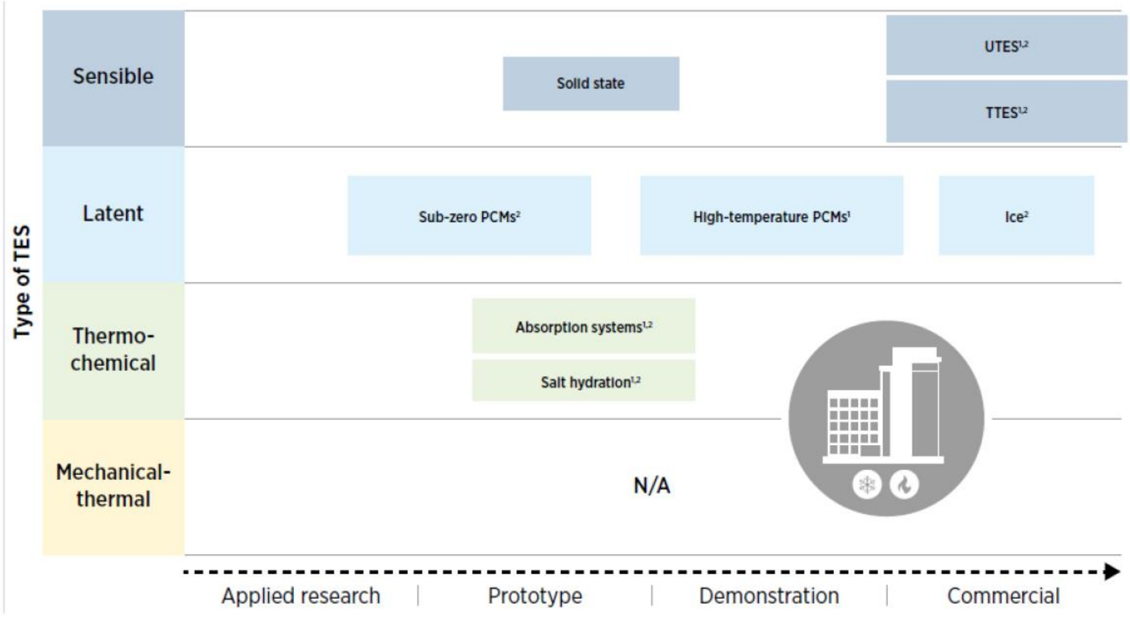
Working principle

Thermal Energy Storage (TES) systems function as reservoirs for excess thermal energy, preserving it for later use when demand arises. They essentially capture surplus energy in a form that can be stored and then release it as needed. TES relies on the concept of converting and storing energy in different mediums, such as the most used medium water, molten salt, or materials that change phase (like from solid to liquid). When there's a need for heat or cooling, the stored energy is retrieved from these mediums and utilized accordingly.

TES systems come in two primary types: sensible heat storage, where the temperature of the storage medium changes, and latent heat storage, where energy is stored through phase change processes. These systems play a crucial role in balancing energy supply and demand, enhancing energy efficiency, and stabilizing energy grids by facilitating the shift of energy consumption to time periods of lower energy demand. They find application across various sectors, including renewable energy integration, HVAC (heating, ventilation, and air conditioning) systems, industrial processes, and large-scale energy storage for power grids and renewable energy projects such as large solar thermal plants.

Current best Practices

Thermal energy storage systems comprise different technologies with various abilities and potentials and can be categorized as follows: sensible, latent, and chemical heat and cold storage (figure 3).



(1) UTES = underground thermal energy storage. TTES = Tank thermal energy storage.

Source: IRENA, 2020.

Figure 3: Commercial readiness level of thermal energy storage systems (source: IRENA 2020).

For district heating networks to be flexible, TES is an essential part of the system. Combining district heating networks with thermal energy storage systems can bring several benefits both in residential, commercial, and industrial applications. By using TES, a higher integration of RES is possible and peak shaving is possible in the network. From a commercial perspective, TES are inexpensive storage systems and can optimize the performance of the DHC system with both emission and cost reductions. Some TES systems can also store heat for larger periods, the seasonal storage systems. Heat stored during the summer period can then be used in the winter to heat buildings. Furthermore, combining a TES system with a cogeneration plant can benefit from higher electricity prizes. Operating the CHP (Combined Heat & Power) when electricity prices are high can give additional income. Energy-intensive processes in industrial applications can also benefit from TES applications and can facilitate further electrification of the industrial sector. Despite all the benefits and the fact that they can play a key role in the EU's energy decarbonization path, the potential of TES has often been overlooked.

As can be seen from the figure above, sensible heat storage (in water) used as daily operation is used commercially ranging from small to very large buffers. The technology has already been used for years and is a cost-effective and proven technology. The only downside is the fact that if a large amount of energy needs to be stored the volume increases drastically.

Latent heat storage system based on PCM and thermochemical storage systems are still in prototype and demonstration projects and have not yet reached the commercial large-scale deployment. These storage technologies can store heat or cold for longer periods than one day and up to several months. Despite the high potential of these storage solutions in energy systems, their market penetration remains limited.

Latest advancements

Latest advancements can be found in large tank and pit storages in combination with large thermal solar fields. Barriers do still exist with this technology with limited spaces in urban aeras and the space needed to implement this large storage volumes. Recent innovations have targeted improvements in the construction methods, the economic feasibility, and the liner material to keep the temperature in the pit at a higher level.

Thermal energy storage in aquifers or water saturated layers is a well-known technology when geological conditions are met. Heat and cold is stored in the underground and can be used in combination with a heat pump system. In the Netherlands and in Belgium several aquifer storage systems are successful in operation for many years. The innovative control of these energy storage systems is investigated in the HEU project push-it (see below).

Latent heat storage has far less heat losses compared to sensible heat storages and their main potential application lies in short-term storage or in district cooling networks with smaller temperature differences. Storage systems based on phase change materials as paraffins, and salts can be applied for different temperature levels (phase change occur at certain temperature level). Their readiness level compared to sensible heat storage is lower and still some technological obstacles need to be overcome e.g., improving the stability of the PCM with thermal cycles, corrosion of the material especially with salt based PCM's, improve the charging / discharging rate, innovative integration with other energy systems, and material science research.

Chemical storage

Two categories of chemical energy storage exist: (1) chemical reversible reactions, utilizing endothermic reactions when excess heat is available (and the opposite when heat is required), and (2) absorption and adsorption, which occurs "when a gas bonds the surface of a solid, respectively creating (absorption) and not creating (adsorption) a new material''. Thermochemical storage systems can be characterized by a high volume, high temperature storage system, and low energy density. Heat losses are low compared to sensible heat storage as the chemical storage material is stored at ambient temperature.

Chemical storage solutions are currently far from being commercially available, but studies show the large potential of this technology. Current research in this field focusses on adaptable and simplified reactor concepts, stabilization of the reactive structure and selection and further development of finding suitable storage materials taken in to account their cycle stability, kinetics, and thermodynamics.

European projects

- **H2020 PUSH-IT.** The PUSH-IT's project ambition is to overcome the seasonal mismatch between heat demand and heat generation from sustainable sources using underground heat storage. The EU project focusses on 3 innovative technologies for high-temperature heat storage, as well as enabling technologies, societal engagement, and governance, policies, and business models. The goal is to develop this missing link in heat networks as a safe, reliable, affordable, and economically viable solution that fits existing and future regulatory frameworks. Link to more information: https://www.push-it-thermalstorage.eu/

- **HEU ECHO.** The EU-funded ECHO project aims to develop an alternative thermal energy storage solution that will be compact, flexible, modular, plug-and-play, sustainable and digitally controlled. A combination of thermochemical materials combined with phase change materials for space heating and cooling, domestic hot water production and ice storage will be developed. Charging of the system will be done via overproduction of electricity from the grid or by directly connecting to renewable energy sources. A heat pump will convert electrical energy into thermal energy. Link to more information: https://cordis.europa.eu/project/id/101096368

- **HEU HEATERNAL.** The EU-funded HEATERNAL project aims to prototype and model a new thermal energy storage concept that can bolster energy density and expedite integration into industrial facilities. The aim of the project is on: (i) innovative phase-change materials and unit designs allowing to increase the unit energy density by 350% versus ceramic bricks, and (ii) manufacturing experience ensuring that materials and units can be rapidly implemented in factories by 2030. Thus, the project will yield a 50kWh prototype (TRL5) and models of the upscaled storage system connected to factories. Link to more information: https://cordis.europa.eu/project/id/101103921

- **HYBUILD.** HYBUILD action is a systematic approach for developing operationally integrated thermal and electric components and systems from TRL4 to TRL6 and beyond. The hybrid storage concepts are based on: a compact sorption storage, based on a patented way to integrate an innovative adsorbent material within an efficient high surface heat exchanger, a high density latent storage, based on a high performance aluminium micro-channel heat exchanger with additional PCM layers, and an efficient electric storage. https://cordis.europa.eu/project/id/768824/fr

- **ECO STOCK. The new environmental energy storage:** With their new technology, ECO STOCK, ETC aims to develop new eco-efficient, transportable and modular thermal storage solutions. https://cordis.europa.eu/project/id/718316/it

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3.4 Thermoelectric generators

Working principle

Thermoelectric Generators (TEGs) are devices that convert heat directly into electricity through the Seebeck effect. Essentially, when there's a temperature difference between the two ends of a thermoelectric material, it generates a voltage. In industrial contexts, TEGs are often placed in areas where there's a notable temperature contrast, such as near machinery or in exhaust systems. Here, the hot side of the TEG comes into contact with the heat source, while the cold side remains cooler or is cooled. As heat moves through the TEG, it produces electric current, which can be utilized to power various devices within the industrial process. By capturing and utilizing waste heat that would otherwise dissipate, TEGs offer a practical means to enhance energy efficiency and decrease operational expenses in industrial setups. Current TEG systems typically have an efficiency range of about 5-10%. This efficiency is determined by several factors, including the properties of the thermoelectric materials used, the temperature gradient across the TEG, and the design of the TEG system.

Latest advancements

Recent advancements in TEGs for waste heat recuperation have significantly improved their efficiency and applicability in industrial processes. Recent developments have pushed TEG efficiencies from the traditional 5-7% range up to 10-12% in some cases, with laboratory-scale systems demonstrating potential efficiencies as high as 15%. Five key aspects are in development to enhance this technology. Firstly, enhanced material efficiency is a major focus. Recent advancements involve developing thermoelectric materials with improved properties, such as higher Seebeck coefficients and lower thermal conductivity. These materials generate more electricity from the same amount of waste heat, thereby increasing the overall performance of TEGs. Secondly, miniaturization and integration techniques have advanced, allowing TEGs to be incorporated into smaller, more compact devices. This miniaturization facilitates the deployment of TEGs in confined spaces within industrial processes, maximizing their potential for waste heat recovery. Smaller TEGs can be placed in various parts of industrial equipment without requiring significant alterations, making them more versatile and easier to implement. Thirdly, flexible, and scalable designs have been introduced, enabling TEGs to conform to various shapes and sizes. These innovations allow TEGs to adapt to irregular surfaces and complex geometries within industrial equipment, improving their efficiency in capturing waste heat. The ability to scale the design ensures that TEGs can be customized for different industrial applications, providing a broader range of solutions for waste heat recovery. Fourthly, improved heat management systems are a significant development. These systems aim to optimize temperature differentials and maximize energy conversion by employing advanced heat sinks, insulation materials, and thermal interfaces. Enhanced heat management minimizes heat losses and improves the overall system performance of TEGs, ensuring that they operate at peak efficiency. Lastly, the integration of TEG systems with Internet of Things (IoT) technology and smart monitoring systems has become increasingly common. This integration allows for real-time performance tracking and optimization, remote monitoring of TEG efficiency, predictive maintenance, and adjustment of operational parameters. IoT-enabled TEG systems provide valuable data that can be used to maximize energy recovery from waste heat and improve the overall efficiency of industrial processes.

Current best Practices

Current best practices for Thermoelectric Generators (TEGs) in industrial applications involve optimizing temperature differentials, selecting efficient thermoelectric materials, integrating systems seamlessly into existing processes, implementing robust monitoring and control systems, and ensuring economic viability through cost-benefit analyses. Continuous research and development efforts are enhancing TEG efficiency, reliability, and scalability for broader adoption in various industries, including steel production.

European projects

- **HRenergycontrol. Minimising energy loss in hot rolling by intelligent manufacturing:** In hot rolling, the primary energy input comes from the latent heat of hot-charged slabs and gases in reheating furnaces, with electricity being the secondary input. Studies show that energy efficiency is less than 40%, with 50% of the total energy loss occurring after the reheating furnaces. This loss mainly involves electricity in rolling stands and coilers, and thermal energy lost through descaling, cooling, and radiation. This proposal aims to minimize energy consumption, define all energy flows in hot rolling, and recover as much energy as possible using low-energy technologies, process optimization, and heat recovery (i.e. thermoelectric generators). https://op.europa.eu/en/publication-detail/-/publication/ab59a7bf-c00f-11e5-9e54-01aa75ed71a1/language-en

- **Inferno. Recycling industrial waste heat through the application of thermophotovoltaic and thermoelectric: A novel hybrid technology for electricity generation**: Energy-intensive high-temperature processing industries lose over 50% of their energy as waste heat annually in Europe, amounting to 200 TWh. INFERNO aims to innovate by developing a hybrid platform integrating thermophotovoltaics (TPV), metasurface collectors (MetaS), and TEGs. This initiative targets a 25% efficiency for new TPV cells with plasmonic metamaterials and 10% for high-performance TEG devices using earth-abundant materials, designed for easy retrofitting into production lines to save energy and reduce greenhouse gas emissions. https://cordis.europa.eu/project/id/101160642

- **Powerstep. Full scale demonstration of energy positive sewage treatment plant concepts towards market penetration:** Municipal wastewater in Europe holds 87,500 GWh/year of chemical energy in its organic fraction, akin to output from 12 large power stations. The POWERSTEP project aims to showcase energy-positive wastewater treatment plants using existing technologies. It will demonstrate innovative processes like enhanced carbon extraction, advanced nitrogen removal, power-to-gas, heat-to-power concepts, and innovative water treatment across 6 full-scale case studies in 4 European countries. These efforts aim to establish wastewater treatment plants as renewable energy sources while enhancing treatment efficiency and sustainability. *https://cordis.europa.eu/project/id/641661*

- **HEAT-R. Waste heat valorization by modular thermoelectric recovery system for resource efficiency in energy intensive industrie.**https://webgate.ec.europa.eu/life/publicWebsite/project/LIFE16-ENV-ES-000344/waste-heat-valorization-by-modular-thermoelectric-recovery-system-for-resource-efficiency-in-energy-intensive-industries

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3.5 High temperature heat pumps

Working principle

A heat pump is a thermodynamic machine that takes low-temperature thermal energy from a heat sink and raises its temperature by means of a refrigeration cycle. There are two macro-categories of heat pump technologies: mechanically driven heat pumps (also known as vapor compression heat pumps) and thermally-driven heat pumps. Vapor compression heat pumps operate on an reverse carnot cycle, where a refrigerant undergoes evaporation and condensation. The cycle involves the following key steps:

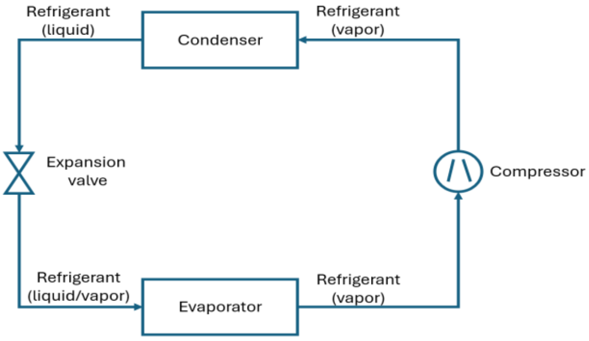

Figure 4: Heat pump cycle steps.

- Compression: The compressor increases the refrigerant's pressure and temperature, changing it from a saturated vapor at lower pressure to a superheated vapor at higher pressure.
- De-superheating and Condensation: In heat exchangers, the refrigerant releases heat and becomes a saturated liquid, providing useful heat to the high-temperature sink.
- Expansion: An expansion valve lowers the refrigerant's pressure and temperature, causing partial evaporation.
- Evaporation: In the evaporator, the low-pressure refrigerant absorbs heat from the low-temperature source, evaporates and leaves slightly superheated to protect the compressor.

Thermally driven heat pumps are mainly based on the absorption technology, which is presented in the following schematic.

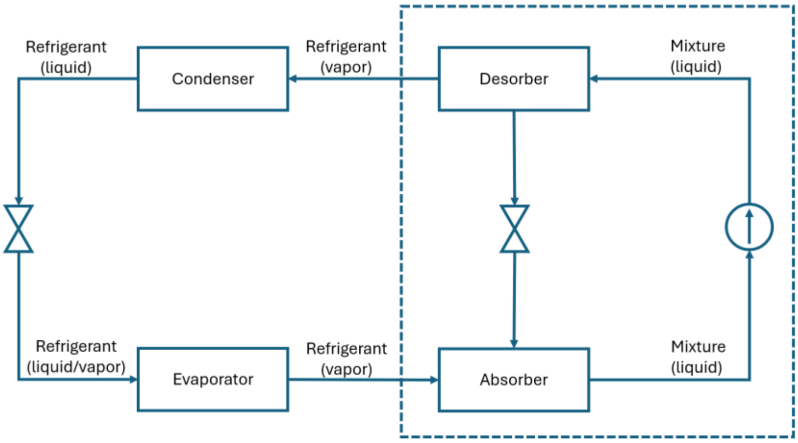

Figure 5: Thermally driven heat pumps based on the absorption technology.

Absorption and desorption allow to work with a liquid mixture (H_2O/LiBr, for high temperature heat source applications, or NH_3/H_2O, in case of low temperature heat source ones) during the compression phase, replacing the use of a compressor with a pump.

Latest advancements

So far, heat pumps have been used exclusively for heating in the residential sector. Few examples of industrial heat pumps for high temperature applications (>100 °C) are appearing in the last couple of years, mainly as pilots and demonstration projects for high-temperature heat pumps; these have primarily focused on vapor compression heat pumps due to their higher technology readiness level.

Industrial high temperature heat pumps are designed to handle significant temperature lifts, usually ranging from 80 °C to 150 °C or more and they can be used for production of hot water or steam. These heat pumps need robust components and materials to endure high temperatures and pressures, making them suitable for sectors like food processing, chemical manufacturing, and waste heat recovery, where high-temperature heat is crucial.

There are two main system of industrial heat pumps; closed systems and open systems.

Closed heat pump systems operate with a sealed loop where the refrigerant continuously circulates. In these systems, heat is absorbed from a source, compressed, released to a sink, and then recirculated. They are commonly used in residential, commercial, and certain industrial applications. Key components of closed systems include the evaporator, compressor, condenser, and expansion valve, which work together to provide controlled and efficient heat transfer without the risk of external contamination.

In contrast, open heat pump systems involve the working fluid interacting directly with the external environment. The fluid is drawn from an external source, compressed, used for heating, and then discharged or recirculated. These systems are predominantly used in industrial settings, such as Mechanical Vapor Recompression (MVR) and steam ejectors. Open systems include components like ejectors and compressors that handle process fluids, making them efficient at recycling waste heat and simplifying the system for industrial applications.

Steam ejectors utilize high-pressure steam to create a vacuum by accelerating a low-pressure vapor through a converging-diverging nozzle, mixing it with the high-velocity steam. The combined mixture is then compressed, converting kinetic energy back to pressure energy. This process effectively removes air and non-condensable gases from systems, commonly used in vacuum distillation, evaporation, and refrigeration. Steam ejectors are simple, reliable, and have no moving parts, making them durable and low-maintenance.

Mechanical Vapor Recompression (MVR) uses a mechanical compressor to elevate the pressure and temperature of vapor, typically from industrial processes. The recompressed vapor is then used as a heat source, providing energy-efficient heating. MVR is commonly applied in evaporation and distillation processes, significantly reducing energy consumption by recycling latent heat. It enhances energy efficiency, lowers operational costs, and reduces greenhouse gas emissions in industrial applications.

Current best Practices

As far as vapour compression heat pumps are concerned, volumetric compressors are used in the case of systems with powers ranging from tens of kW to 1 MW. For outputs above 1 MW, turbo-compressors are used instead.

Selecting the best working fluid for high-temperature heat pumps requires balancing several critical factors:

- Pressure: The fluid should have moderate pressure, ideally above atmospheric but not excessively high, at typical operating temperatures for evaporation and condensation.
- Heat Transfer Performance: Essential properties include low viscosity for easy flow, high thermal conductivity for effective heat transfer, and a high latent heat of phase change for efficient thermal energy exchange.
- Compressor Efficiency: An efficient compressor allows to increase the performances of the heat pump, reducing energy consumption.
- Safety and Environmental Considerations:
  - Safety: The fluid should ideally be non-flammable to reduce risks.

  - Environmental Impact: Fluids should have zero ozone depletion potential and low global warming potential,and be compatible with most materials to ensure system integrity and minimize environmental impact.

No single fluid excels in all these areas, so based on specific application needs, a trade-off choice should be done. However, enhancing the system efficiency is crucial, in particular because of the continuous long-term operation of industrial high temperature heat pumps.

European projects

- **HEU Push2heat**. The project aims to overcome the barriers to the deployment of heat pump technologies for heat upgrading in the industrial sector. Push2Heat is an EU-funded project that aims at addressing the technical, economic, and regulatory barriers that prevent heat upgrading technologies from being widely deployed. It will do so by scaling up four different technologies (whose supply temperatures range from 90 °C to 160 °C) to optimize their efficiency and economic performance. In addition, it will focus on integrating them into the relevant industrial sectors such as the paper and chemical industries. The four technologies will then be demonstrated in selected industrial sites. The project will also work towards demonstrating suitable business models and dedicated exploitation roadmaps for higher market penetration of heat upgrading technologies. Link to more information: https://push2heat.eu/ .

- **HEU Spirit**. The EU SPIRIT project plans to take advantage of waste heat source, building three full-scale (> 0.7 MWth) demonstration systems of industrial heat pumps that upgrade waste heat to valuable temperatures (135 - 160 °C). The demonstration covers sites in the paper & pulp and food & beverage industry, covering 63% of the potential high-temperature heat upgrade market. SPIRIT achieves technology scaling by designing modular heat pumps with standard components covering a large portion of the industrial heat upgrade market. Link to more information: https://spirit-heat.eu/ .

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3.6 Electrolyzers

Working principle

Industrial electrolyzers function by using electrical energy to drive the chemical process of splitting water into hydrogen and oxygen. The system comprises two electrodes—an anode and a cathode—immersed in an electrolyte. When a voltage is applied, water molecules undergo electrolysis, with hydrogen gas being produced at the cathode and oxygen gas at the anode. The efficiency of this process depends on several factors including the electrode materials, the type of electrolyte, and the operating conditions such as temperature and pressure.

Latest advancements

Recent advancements in electrolyzer technology have focused on improving efficiency, reducing costs, and enabling large-scale hydrogen production. Significant progress has been made in developing new electrode materials, such as advanced nanomaterials and transition metal catalysts, which offer higher efficiency at lower costs. High-temperature electrolysis, particularly with solid oxide electrolyzers (SOE), has shown promise by operating at elevated temperatures (700-1000°C), which enhances efficiency and reduces energy requirements. Pressurized electrolyzers are also being developed to produce hydrogen at higher purity, thus reducing the need for subsequent compression. Additionally, modular and stackable electrolyzer designs facilitate easy scalability to meet industrial hydrogen demands.

Improvements in membrane technology, particularly proton exchange membranes (PEM), have enhanced the durability and conductivity of electrolyzers, contributing to better performance and longevity. Hybrid systems that integrate electrolyzers with renewable energy sources, such as wind and solar power, are being explored to provide sustainable and carbon-neutral hydrogen production. Advanced automation and control systems utilizing real-time data analytics and machine learning algorithms are optimizing electrolyzer operations, ensuring consistent performance and predictive maintenance.

Current best Practices

Current best practices for industrial electrolyzers focus on maximizing efficiency, ensuring safety, and integrating seamlessly with existing industrial processes. Optimal operating conditions, such as maintaining ideal temperature, pressure, and voltage, are crucial for maximizing efficiency and the lifespan of electrolyzers. Regular maintenance, including routine inspections and component replacements, helps prevent failures and maintain consistent performance. Implementing robust safety protocols is essential to handle hydrogen safely, given its highly flammable nature. Proper ventilation and leak detection systems are standard practices to mitigate risks.

Incorporating electrolyzers with renewable energy sources helps to utilize excess power during peak production times, reducing reliance on fossil fuels. High-purity water is used to prevent contamination and scaling, which can affect electrolyzer efficiency and durability. Energy recovery practices, such as using waste heat from high-temperature electrolyzers in other industrial processes, enhance overall energy efficiency. Advanced control systems dynamically adjust operational parameters based on real-time data to optimize performance, while thorough economic analysis ensures the feasibility and profitability of deploying electrolyzers in specific industrial contexts. Ensuring environmental sustainability throughout the entire process, from sourcing raw materials to managing emissions, is also a key consideration.

By focusing on scalability and flexibility, industrial electrolyzers can be adapted to various settings, making them a versatile solution for hydrogen production in the transition to a more sustainable energy future.

European projects

- **REFHYNE**. **Clean Refinery Hydrogen for Europe:** The REFHYNE project will install and operate a 10MW electrolyser from ITM Power at a large refinery in Rhineland, Germany, which is operated by Shell Deutschland Oils. The electrolyser will provide bulk quantities of hydrogen to the refinery's hydrogen pipeline system (currently supplied by two steam methane reformers). The electrolyser will be operated in a highly responsive mode, helping to balance the refinery's internal electricity grid and also selling Primary Control Reserve service to the German Transmission System Operators. Demonstrates the feasibility of large-scale hydrogen production using PEM electrolyzers integrated with renewable energy. https://www.refhyne.eu/

- **H2FUTURE**. **Hydrogen meeting future needs of low carbon manufacturing value chains:** Under the coordination of VERBUND, VOESTALPINE and SIEMENS propose a 26-month demonstration of a 6MW electrolysis power plant at VOESTALPINE's LINZ plant in Austria. The electrolyser, prequalified with APG's support, aims to provide grid-balancing services while utilizing VERBUND's commercial pools. The demonstration involves five pilot tests and quasi-commercial operations to prove the PEM electrolyser's effectiveness in utilizing power price opportunities and generating extra revenues from grid services. The project's replicability across EU28's steel industry is assessed under ECN's coordination, with technical, economic, and environmental evaluations using CertifHY tools. The creation of an exploitation company ensures commercial operations post-demonstration, and dissemination efforts target European stakeholders to facilitate broader implementation over the next decade. https://www.h2future-project.eu/

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3.7 Organic Rankine Cycle

Working principle

The Organic Rankine Cycle (ORC) is a thermodynamic process designed to convert low-grade heat into mechanical work, which is then transformed into electricity. Unlike the traditional Rankine cycle that uses water as the working fluid, the ORC uses organic fluids with low boiling points, making it ideal for exploiting low-temperature heat sources like industrial waste heat, geothermal energy, and solar thermal energy. In an ORC system, heat from a source is transferred to the organic working fluid in an evaporator, where the fluid absorbs the heat and vaporizes. The high-pressure vapor then expands through a turbine, converting thermal energy into mechanical work. This mechanical work drives a generator to produce electricity. After expanding, the vapor enters a condenser, where it releases its heat and condenses back into a liquid. This liquid is then pumped back to the evaporator, completing the cycle. ORC systems are valued for their efficiency at low temperatures, scalability, and flexibility, with reduced maintenance requirements due to the less corrosive nature of organic fluids.

Latest advancements

Recent advancements in ORC technology have focused on enhancing efficiency and expanding the range of applications. Innovations in working fluids have led to the development of new organic compounds that optimize performance and thermal stability. Advances in turbine design, including the use of high-speed microturbines and variable geometry turbines, have improved energy conversion efficiency. Integration with other renewable energy systems, such as combining ORC with biomass or solar thermal power, has broadened its application scope. Additionally, improvements in heat exchanger technology have enhanced the effectiveness of heat transfer processes. Enhanced control systems, utilizing real-time data and machine learning, now allow for more precise operation and maintenance, further increasing system efficiency and reliability.

Current best Practices

Current best practices for ORC systems focus on maximizing efficiency and reliability through optimized design and operation. Selecting the appropriate working fluid based on the specific heat source characteristics is critical for performance. Advanced heat exchanger designs that enhance heat transfer efficiency are employed to improve the overall cycle efficiency. Regular monitoring and maintenance, facilitated by sophisticated control systems, ensure optimal operation and longevity of the ORC components. Integrating ORC systems with existing industrial processes for waste heat recovery has become a common practice, providing significant energy savings and reducing carbon emissions. Utilizing hybrid systems, where ORC is combined with other renewable energy sources, has also proven effective in increasing the energy yield and sustainability of power generation setups.

European projects:

- **ORC-PLUS. Organic Rankine Cycle - Prototype Link to Unit Storage:** ORC-PLUS aligns with H2020-LCE-03-2014 by enhancing renewable energy system performance, reducing costs, and improving dispatchability. It aims to optimize TES for small Concentrated Solar Power (CSP) plants (1-5 MWe) in desert regions, coupled with an ORC system. Enhanced TES extends energy production beyond solar hours, minimizing the need for fossil or renewable fuels in backup systems. While current R&D focuses on large-scale CSP, ORC-PLUS targets small to medium-scale installations with significant potential. The project advances from large-scale prototypes to pre-commercial demonstrations, integrating solar fields, ORC units, and innovative TES technologies validated through industrial pilot plants (TRL 6-7), ensuring techno-economic viability and environmental impact analysis. https://cordis.europa.eu/project/id/657690

- **Supercritical-ORC. Development of a small-scale low-temperature Supercritical Organic Rankine Cycle engine with optimised scroll expander and evaporator**: The project titled “*Development of a small-scale low-temperature Supercritical Organic Rankine Cycle engine with optimised scroll expander and evaporator*” in the framework of the program “SYNERGASIA

2011", aims to develop and bring into the market a small scale (5-10 kW) low temperature (80-100 ºC) SuperCritical Organic Rankine Cycle (SCORC) engine, so that the huge potential of low temperature thermal sources (such as waste heat, geothermal energy, solar energy, etc.) to be efficiently and cost effectively exploited for power generation. The main technological innovation concerns the operation of the engine at supercritical conditions, requiring a detailed investigation of the main processes, in order to maximize the system performance. http://supercritical-orc.aua.gr/

- **SO-LNG-ORC. Integrated Organic Rankine Cycle system for simultaneous utilization of solar energy and LNG cold energy**: Researchers carried out simulations to determine the optimal design of the two-tank thermal energy storage system and the most suitable temperatures of the hot and cold storage tanks. Furthermore, they investigated the optimal mass flow rates of the heat transfer fluid, which determine both the temperature of the circulating fluid and the heat absorbed by the solar thermal collector. The ORC system driven by solar energy generated round-the-clock stable power output. https://cordis.europa.eu/project/id/891561

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4 Conclusions

In summary, the recent advancements in energy efficiency technologies highlighted in this document are paving the way towards a more sustainable future. These innovations leverage digitalization, advanced materials, and smart technologies to optimize energy consumption across residential, commercial, and industrial sectors. By harnessing waste heat, integrating renewable energy sources, and enhancing operational efficiencies through sophisticated control systems and predictive algorithms, these technologies are not only reducing greenhouse gas emissions but also driving economic benefits. These technological advancements underscore a critical shift towards sustainable energy practices, enhancing energy security, reducing dependence on fossil fuels, and mitigating climate change impacts. As these technologies continue to evolve and become more widespread, they hold the potential to fundamentally transform how we produce, distribute, and utilize energy, thereby contributing to a cleaner and more resilient energy future globally. Continued research, development, and deployment efforts will be crucial in realizing their full potential and accelerating the transition towards a sustainable energy ecosystem.

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