RE-WITCH

The coolest cold from
the cleanest heat

First release of industrial cooling needs and RE-WITCH technology specifications

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About

The overarching aim of RE-WITCH, a project funded by the European Horizon programme, is to deliver cost-competitive, game-changing solutions in the field of sustainable industrial cooling and heating. To do so, RE-WITCH will demonstrate advanced thermally driven industrial cooling technologies based on ADsorption and ABsorption processes driven by an optimized mix of low-grade waste and renewable sources (innovative high vacuum flat plate solar collectors).

Such solutions will be demonstrated in 4 demo sites (3 confirmed as of January 2024, in Greece, Spain and Poland) encompassing Food and Drink sectors as well as industrial sectors where heat-to-cold solutions are not yet widely explored (bio-refinery). The activity will be completed by studying the replicability of proposed technologies in replication sites even integrated with District Heating Networks (DHN).

The project will be delivered by an industrial-driven consortium of 26 partners from 10 countries and it is composed by some of the most innovative SMEs, LEs and R&D centres in the field of industrial renewable H&C leveraging experience from industrial and EU-funded projects (HYCOOL, SO-WHAT, Indus3Es).

The multi-disciplinary composition of the consortium ensures that all the challenges (technical and non-) will be addressed to ultimately bring RE-WITCH solutions to the market by 2029. Innovative open access modelling platforms and engineering solutions will also be developed to facilitate the design, upscale, replication and integration in industrial processes of the proposed technologies. Thanks to a stakeholders' driven dissemination and communication campaign, RE-WITCH will ultimately demonstrate transformative technological solutions that unlock the combined potential of low-grade waste and renewable heat use in industries, hence also targeting integration of heat-to-cold technologies into relevant EU policies.

Project partners

ITAE Consiglio Nazionale delle Ricerche
ivl Swedish Environmental Research Institute
baelz automatic
CiaoTech by PNO Group
Cartiera dell'Adda S.R.L.
dr. jakob energy research
IDP ingeniería · medio ambiente · arquitectura
OST Ostschweizer Fachhochschule
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FPI Food-Processing Initiative e.V.
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Gruppo SIGLA esperienza ed innovazione
University of Birmingham
TVP Solar
STAM Mastering Excellence
HM Hochschule München University of Applied Sciences
Gradyent
COVAP
Sorption Technologies
IEECP Institute for European Energy and Climate Policy
Università di Genova
Lithuanian Energy Institute
miloil

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Abbreviations

°C	Degrees Celsius
a	Annually
AHU	Air Handling Unit
CHP	Combined Heat and Power
COP	Coefficient of Performance
CPS	Cooling Process and Spaces
CWT	Cooling for Water in Water Treatment in Textile
DC	Deep Cooling
EU	European Union
EUR	Euro (currency)
FAME	Fatty Acid Methyl Esters
gal	Gallon
HVAC	Heating, Ventilation, and Air Conditioning
kg	Kilogram
LiBr	Lithium Bromide
mol	Mole
RFS	Refrigeration for Food Storage
t	Tonne
th	Thermal Energy

toe	Tonne of Oil Equivalent
TRL	Technology Readiness Level
W	Watts
Wh	Watt hour

1. EXECUTIVE SUMMARY

This deliverable presents a background study conducted as part of the RE-WITCH project, funded by the European Union (EU) Horizon program (grant agreement number 101138697). The project aims to develop innovative and efficient thermally driven cooling and heating technologies for industrial processes, optimising the use of low-grade waste and renewable heat through new generation of adsorption and absorption chillers.

Cooling demand and the availability of waste heat sources are analysed, including renewable energy systems, in key industrial sectors: Food & Drink, Pharmaceutical, Bio-fuels, and Pulp & Paper. It characterises specific industrial processes (archetypes) within these sectors, focusing on key cooling demand parameters such as temperature levels and total energy consumption.

Firstly, sectorial cooling demand is analysed based on data from literature. The Food & Drink sector demonstrates the highest cooling demand with the lowest temperature requirements, while the Bio-fuel sector exhibits the lowest demand. Detailed archetype descriptions follow, highlighting key processes within each sector. For the Food & Drink industry, dairy and beer processes are analysed. In the Pharmaceutical sector, ointment oil production serves as the archetype. The Kraft pulp-making process is selected for the Pulp & Paper sector, and biofuel archetypes are based on widely reported production method. These descriptions illustrate that the lowest cooling temperature, approximately 4°C, is required in dairy and beer production.

This deliverable also outlines the basic requirements for adsorption and absorption technologies in these sectors. Adsorption systems, leveraging solid sorbents and low-grade heat, can achieve high efficiency with thermal and electric coefficient of performances (COPs) of 0.65 and >20, respectively, while ensuring compactness and cost-effectiveness. Absorption systems utilise lithium bromide-water pairs and innovative hybrid designs to address limitations such as crystallisation risk and narrow temperature ranges.

Overall, this deliverable provides a comprehensive analysis of industrial archetypes and evaluates their suitability for RE-WITCH technologies.

2. INTRODUCTION AND SCOPE OF THE DELIVERABLE

This deliverable serves as a background study for the RE-WITCH project, funded under the EU Horizon programme, grant agreement number 101138697. The project aims to develop cost-competitive, sustainable-by-design cooling solutions that maximise the reuse and recycling of waste heat while unlocking the potential of low-grade waste and renewable heat utilisation in the industrial sector. To achieve this, new generation adsorption and absorption cooling technologies will be developed and demonstrated across four demo sites in the Food & Drink, Pulp & Paper, and Biofuel sectors.

Industrial processes are energy-intensive, with heat and cooling demands constituting a significant portion of total energy consumption. In the EU, industrial energy demand exceeds 3000 TWh annually, with heat requirements accounting for about 60% of this total. Process heat, often provided through hot water, steam, and hot air, represents 80% of industrial heat demand. Conversely, cooling demand in industrial applications, accounting for approximately 78% of Europe’s total cold production, in sectors such as Food & Drink, which rely strongly on cooling for thermal conservation and process efficiency. Figure 1 shows the energy consumption of industrial sectors in 2022 in European countries [1].

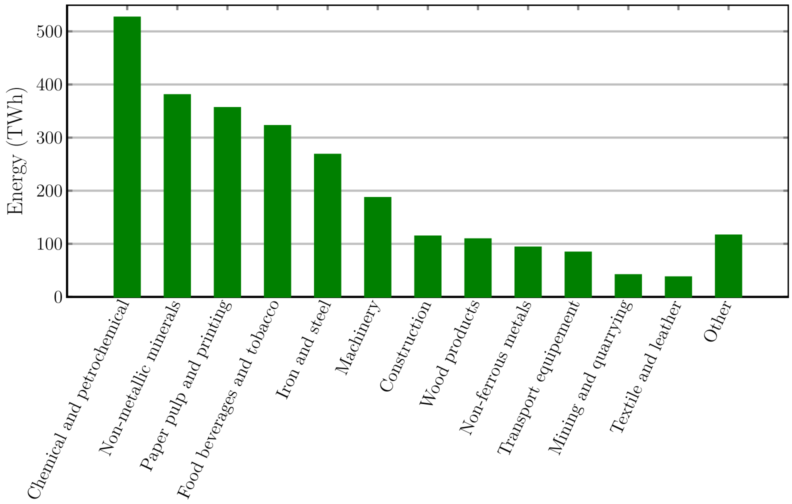


Figure 1 Total final energy consumption by industrial sector in Europe 2022 [1].

The temperature ranges of industrial processes play a critical role in determining waste heat recovery and utilisation potential. Waste heat, defined as energy generated during industrial processes but not utilised, is released at varying temperatures. The greatest potential for recovery lies in processes that operate between 100 °C and 200 °C, common in the Food & Drink, Paper, and Wood industries. Processes requiring heat below 200 °C often produce waste heat close to ambient temperatures, making recovery and reuse challenging without advanced thermally activated technologies (TATs) such as those based on Adsorption and Absorption processes. Table 1 and Table 2 show the levels of process temperature of most relevant sectors regarding heat and cooling demand, respectively.

Table 1 Industrial process with hot temperatures.

Industry	Process	Temperature (°C)
Food	Cleaning	60
	Blanching	60 – 90
	Pasteurisation	80 – 95
	Boiling	95 – 105
	Cooking	110 –115
	Sterilisation	110 – 150
Chemical	Compression	110 –170
	Distillation	110 – 300
	Thermoforming	130 –160
Paper	Pellet drying	95 – 120
	Pressing	100 – 160

Table 2 Industrial processes with cold temperature.

Industry	Process	Temperature (°C)
Food/Chemical	Freezing	-10 – 0
Food/Plastic/Chemical	Refrigeration	0 – 4
	Cooling	4 – 10
Textile	Cooling for wastewater treatment	10

This deliverable examines the industrial sectors targeted by the RE-WITCH project, focusing on their energy demands and the temperature levels of cooling requirements. By identifying archetypes for key industrial processes, the report evaluates the suitability of RE-WITCH technologies: Adsorption and Absorption chillers, which are well-suited for valorising low-grade waste heat. Absorption chillers, already a mature technology, provide reliable cooling exploiting waste heat sources in temperature ranges from 70 °C to 200 °C, while adsorption chillers excel at even lower temperatures, demonstrating high potential for sectors like Food & Drink and Pharmaceuticals. Additionally, absorption heat transformers (AHTs) can efficiently recover heat for high-temperature applications, expanding the applicability of thermally activated systems.

By addressing the integration of these technologies into industrial operations, this deliverable provides a foundational analysis for their application. The RE-WITCH project aims to transform waste heat into valuable energy resources, reducing energy waste and enhancing industrial sustainability across Europe.

3. RE-WITCH RELEVANT INDUSTRIAL SECTORS AND THEIR KEY CHARACTERISTICS

3.1. FOOD AND DRINK

The Food and Drink industry in the EU-27 reached an annual turnover of EUR 1,112 billion and provided 4.6 million jobs in 2023, establishing it as the largest manufacturing sector in the region. In half of the EU-27 member states, it stands as the leading manufacturing employer [2]. The sector is notably fragmented, comprising over 291,000 companies – about 290,000 of which are small and medium-sized enterprises (SMEs) (see Figure 2). SMEs contribute nearly half of the industry's turnover and account for two-thirds of total employment in the sector [3]. Additionally, Europe's food industry is largely localized, sourcing approximately 70% of its agricultural inputs from within the EU. This industry diversity, reflected in its broad array of products and processes, is partly due to the unique food traditions and production scales in each country.

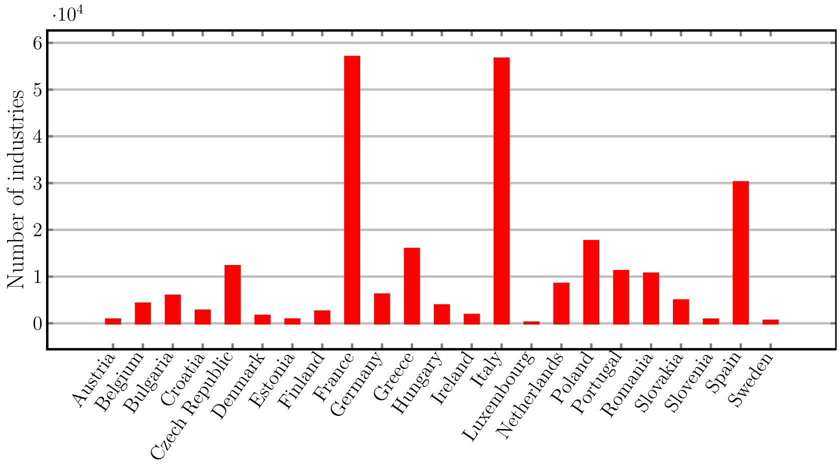


Figure 2 Number of Food and Drink industry by country (Europe).

The Food and Drink sector encompasses a wide range of products, with manufacturing processes that require diverse raw materials and involve multiple production steps. It is also a significant energy consumer; in 2022, it accounted for 25.1% of Europe's total energy consumption, driven by the extensive energy required for cultivation, processing, packing, and distribution [4]. Table 3 details the thermal and electrical energy consumption required to produce a ton of product across six European countries: Austria, France, Germany, Poland, Spain, and the United Kingdom [5], [6]. Electricity use in the sector is largely driven by cooling systems, which represent about 31% of the total consumption [7] (see Figure 3).

Table 3 Thermal and electrical energy per ton of product in six European countries (mean; range in brackets). [5], [6].

Branch/product	Thermal energy (kWh/t)	Electrical energy (kWh/t)
Bakeries	1335 (243-3039)	590 (150-1834)
Beverages	317 (56-1950)	253 (14-800)
Dairy	1055 (129-3957)	625 (21-3636)
Fruits and vegetables	459 (124-1235)	253 (85-1235)
Meat	510 (20-1668)	354 (77-957)
Beer	373 (0-1950)	219 (52-800)
Sugar	1759 (1398-3076)	282 (185-560)
Slaughtering	155 (0-343)	326 (77-953)
Meat Processing	612 (20-1668)	366 (85-957)

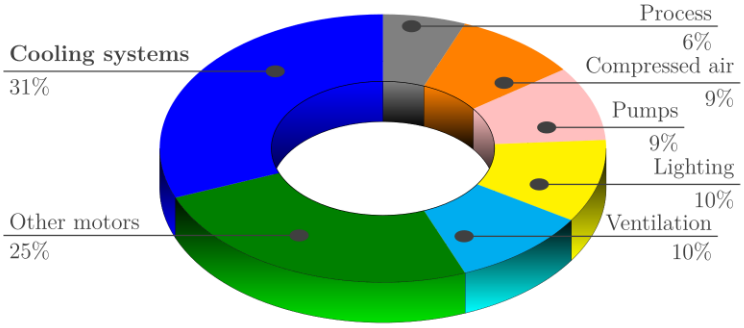


Figure 3 Share of electricity consumption of cross-cutting technologies in the food and drink manufacturing sector [7].

Cooling demand in the Food and Drink industry is characterised by high intensity, variable loads, and low temperatures. Critical for temperature-sensitive processes such as chilling, freezing, and storage, the industry generally requires cooling within a range of -20 °C to 10 °C, depending on specific product needs. Some facilities, particularly in meat and dairy processing, require continuous cooling to maintain temperatures below 5 °C, preserving product quality and safety. The demand for low-temperature cooling (0-15 °C) in the European food industry alone is estimated at approximately 66 TWh annually [8].

For instance, in meat processing, with cooling and refrigeration being the largest contributors. Poultry meat processing is the most energy-intensive, requiring 860 kWh/t (dress carcass weight), followed by pork at 582.5 kWh/t, and beef, veal, and sheep at 386 kWh/t [9] . Essential processes like chilling, freezing, and cold storage can comprise up to 50% of a meat processing plant’s total energy use.

In winemaking, cooling plays a crucial role during fermentation, regulating temperature to ensure product quality. For instance, a regional winery located in Adega da Ervideira (Portugal) operates a 149 kW central chiller to manage heat generated during fermentation and aging, with total refrigeration needs estimated at 96.2 MWh/a which means 12 MWh/a per 100 000 bottles of wine (assuming a volume of 75 cl of the bottle: 165kWh/t)[10].

In dairy production, cooling is critical for maintaining milk quality, accounting for approximately 31% of dairy farm’s total energy consumption [11]. Raw milk is typically cooled to around 4 °C immediately after milking to inhibit bacteria growth. Additional energy is consumed for water heating, necessary for cleaning and sterilisation, which constitutes 23% of total energy use, while vacuum pumping for milking accounts for 20% [12]. Milk cooling requires 10.9 Wh/kg, and energy intensity for processing raw milk in dairy plants ranges from 0.22 kWh/kg to 0.52 kWh/kg [13][14][15]. In cheese production, energy intensity varies significantly, from 2.33–2.66 kWh/kg in the United States to 1.36 kWh/kg in the Netherlands, due to local climate differences.

Food and Drink manufacturing facilities commonly employ industrial refrigeration units, evaporative coolers and combined heat and power (CHP) systems with absorption chillers. CHP systems are especially advantageous, as they provide heat and power, enabling efficient energy management. Absorption chillers are employed in the Food and Drink industry, utilising heat generated as a by-product in CHP systems to provide low-temperature cooling. These systems effectively address intermittent cooling demands and reduce peak loads, aligning with the objectives of RE-WITCH project [16].

3.2. PULP AND PAPER

Different types of pulp, derived from virgin wood or recycled materials, are used to produce various grades of paper products (see Figure 4). According to statistics [17], 856 Pulp & Paper mills were operating across Europe in 2023. On a global scale, Asia is the largest producer and consumer of Pulp & Paper, with China leading in both production and consumption; Asia accounts for approximately 50% of global paper production [18]. Europe contributes about 20% to global pulp production, with Sweden and Finland as the leading producers.

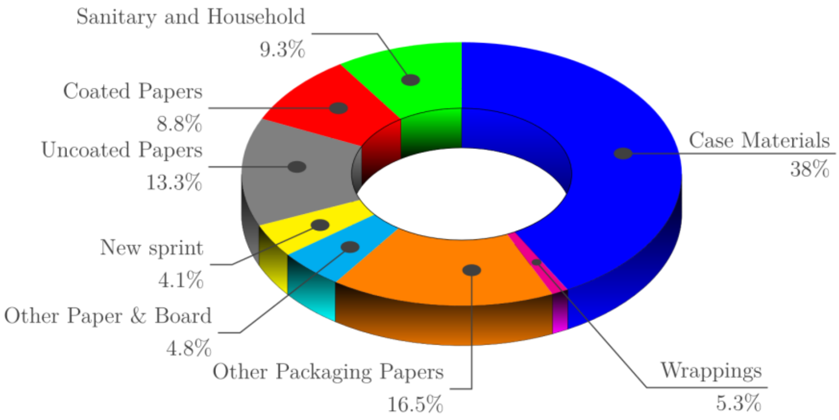


Figure 4 Production of paper and board by grade in CEPI countries in 2022 [19].

Paper production involves a two-step process: first, converting fibrous raw materials into pulp, and second, transforming the pulp into paper. In pulping, wood fibres are separated through either mechanical or chemical methods [20]. Mechanical pulping primarily involves physical separation of cellulose fibres through energy-intensive grinding and refining techniques, such as refiner mechanical pulping and thermomechanical pulping. These processes involve steaming and refining the raw material to extract fibres. Chemical pulping, on the other hand, includes steps such as wood yard operations, pulping, washing, screening, chemical recovery, pulp beaching, pulp drying, and paper formation. It is the dominant method in the pulp and paper industry, responsible for over two-thirds of global wood pulp production [21].

There are three main grades of wood pulp used in European papermaking [19]: sulphate pulp constitutes 60% of total production, mechanical and semi-chemical pulp 32%, and sulphite pulp 5%. Excluding paper production facilities, Europe has 192 pulp mills. Most sulphate pulp production is concentrated in Sweden and Finland, with 38 mills in total. Sulphite pulp production, primarily in Sweden, Germany, and Austria, involves 16 mills, with smaller facilities in five other countries. Mechanical pulp processing, utilised in 72 mills, is mainly concentrated in Finland, Germany, Sweden, Norway, France, Italy, and Austria. The primary producers of semi-chemical pulp (18 mills) are Sweden, Finland, Italy, and the Netherlands, with a few additional mills across other countries. In terms of paper mills, Italy and Germany have the highest number, with around 180 paper mills each.

In 2022, the Pulp & Paper industry in Europe produced approximately 84.5 million tons of paper, board, and cardboard. In 2021, the sector consumed about 105 GWh of energy, representing 11.5% of industrial energy used and ranking as the fourth-largest consumer [22]. In 2022, industrial energy consumption declined by around 8%, with the Pulp & Paper industry consuming about 98.6 GWh, making it the third-largest industrial energy consumer in Europe, following the chemical and petrochemical industry, and non-metallic minerals industry.

The main energy consumption in Pulp & Paper production stems from heat supply and power. Around 93% of total energy use is in the form of heat, primarily for generating pressurised steam, while 7% is electricity [22]. Thermal energy consumption varies significantly based on production technology, paper grade, and fibre quality. Kraft pulping, for instance, has the highest energy demand at 7.3 MWh/t – about 1.4 times more than other methods like sulphite, thermomechanical, and mechanical pulping, and 8.3 times higher than energy used for repulping recycled paper (0.88 MWh/t). Electricity consumption also varies, from 1.23 MWh/t for virgin wood pulp to 0.35 MWh/t for recycled paper pulp [22].

In the Pulp & Paper industry, cooling is essential for process temperature control, particularly in stages such as black liquor evaporation, bleaching, and drying. Cooling is required to regulate the temperature of products, machinery and equipment, including engines, transformers, condensers, and compressors, as well as for air conditioning [23]. Closed-loop water systems and evaporative cooling towers are the most common cooling systems used in the industry [24]. Although detailed data on total cooling demand is scarce, site-specific estimates have been reported. For example, in a plant with an average output of 700 ADT/d (air-dried tons) of high-grade bleached pulp, minimum heat requirements are about 123 MW, with a minimum cooling requirement of 10 MW [25]. In Germany for instance, the largest cooling demand in the Pulp & Paper industry is driven by air conditioning requirements within production facilities. Process cooling demands reach approximately 90 GWh per year (electrical energy for cooling process), with an estimated total cooling demand of 252 GWh annually [26].

3.3. PHARMACEUTICAL INDUSTRY

In 2021, Europe's pharmaceutical industry achieved a trade balance of 175 billion EUR and employed approximately 840,000 people [27]. The distribution of pharmaceutical production across European countries is shown in Figure 5. The chemical and petrochemical sectors remain heavily dependent on natural gas; in 2022, chemical production consumed 154 TWh of natural gas, accounting for 32.6% of the sector's total energy use. Meanwhile, the manufacture of basic pharmaceutical products and pharmaceutical preparations used 11.9 TWh of natural gas, or 36.5% of the total energy consumption within this sector (Pharmaceutical). Electricity ranked as the second most critical energy source for chemicals (30.2%) and was the first source for pharmaceuticals (44.5%) [4]. The energy consumption of major pharmaceutical companies, including Sanofi, GSK, and Johnson & Johnson, exceeds 3 TWh/y (see Figure 6), with an energy intensity of about 0.6-1.0 kWh per 10 EUR of sales. Heating, ventilation, and air conditioning (HVAC) systems typically account for over 50% of total energy consumption in this industry [28][29].

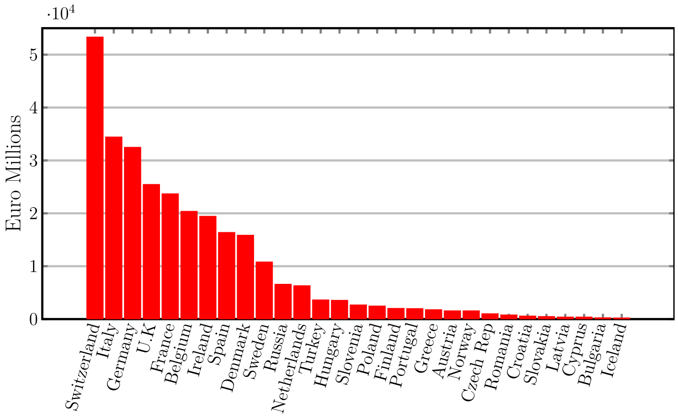


Figure 5 Pharma producing countries in Europe [27].

The pharmaceutical industry is highly energy-intensive, with consumption metrics varying widely across facilities and processes. A study of 84 Italian pharmaceutical plants revealed an average primary energy consumption of approximately 0.38 tons of oil equivalent per square meter of plant surface area (toe/m^2). This corresponds to around 4.4 MWh/m^2. The study found that roughly 70% of energy use in these facilities is used by auxiliary services (i.e heat and cold energy production, AHUs, water purification, air compression and water pumping), especially HVAC systems, which are critical for maintaining controlled environments [30]. Additionally, about 50% of the final energy consumed in these facilities is in the form of heat or cooling, with approximately 30% of electricity usage dedicated to generating cooling energy.

Temperature control is vital in pharmaceutical manufacturing to ensure product quality and regulatory compliance. Cleanrooms, which are common in pharmaceutical production, generally maintain temperatures between 17 °C and 25 °C, depending on process requirements. These controlled environments are essential for preventing microbial contamination and ensuring product stability [31]. Cooling loads in pharmaceutical facilities are significant, driven by equipment heat output, lighting, and occupancy, and HVAC systems play a central role in maintaining these conditions. In some cases, refrigeration can account for up to 90% of a facility's energy costs, particularly in processes requiring stringent temperature control [32].

For instance, a regional pharma manufacturing site located in Rovereto, autonomous province of Trento in Italy, supplies heat via a saturated steam network at 165 °C, while cooling demands are met using mediums at -7 °C of 10 °C. Combined heat and power (CHP) systems with reciprocating internal combustion engines provide an electrical capacity of 4.5 MW$_{el}$ and 13.5 MW$_{th}$. Additionally, natural gas boilers with a capacity of 26 MW$_{th}$ can supply heating when needed [35].

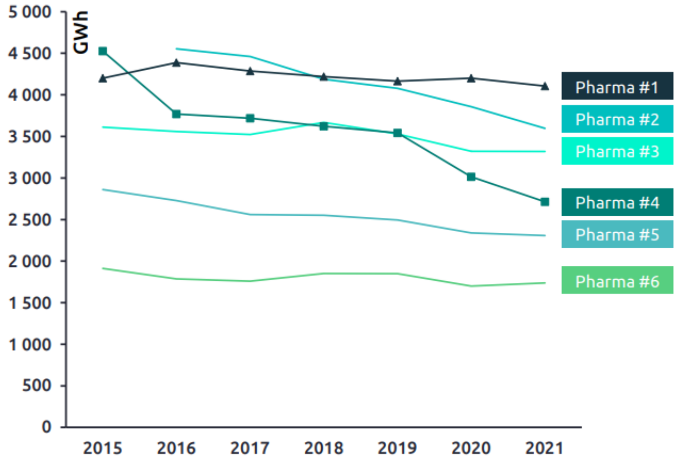


Figure 6 Energy consumption and energy intensity of six major global Pharma companies [28].

3.4. BIO-FUELS

In 2023, the EU produced approximately 19.02 million metric tons of biodiesel, a slight decline from over 20 million metric tons in 2022 [36]. Germany led in production, generating over four billion litres of FAME (fatty acid methyl ester) biodiesel, followed closely by France. Figure 7 shows the production of solid biofuels in the top 10 European countries measured in Mtoe.

The energy consumption in biodiesel production depends largely on the feedstock. For example, biodiesel from oil and algae requires an energy intensity of 0.12 kWh/l [37] and 143.1 kWh/kmol, respectively [38]. When biodiesel is produced from a mixture of sodium hydroxide, methanol, and fresh oil, the energy intensity can reach 1.7 kWh/kg.

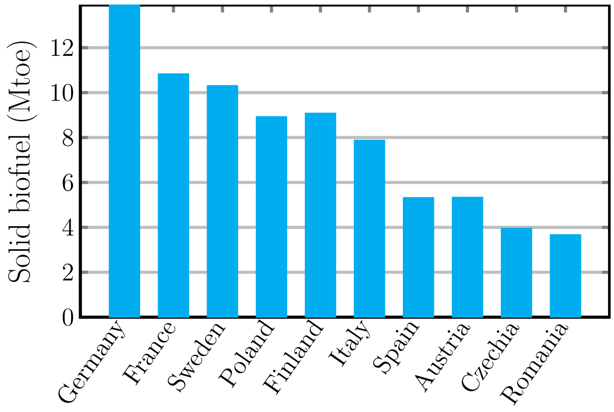


Figure 7 Primary energy production of solid biofuel in 2021 [39].

The primary reactions in biodiesel production are esterification/transesterification of free fatty acids or triglycerides with alcohol, which can involve both catalytic (chemical and biological) and non-catalytic processes. During the transesterification process direct drive fans are employed to maintain homogenous high temperature. In continuous-flow production, even short disruptions can be highly costly, underscoring the importance of robust cooling systems to maintain optimal temperatures at critical production stages. For instance, in a biodiesel plant with an annual production capacity of 13,000 tonnes, six open-loop cooling towers with a total cooling capacity of 13.95 MW are required [40].

4. RE-WITCH RELEVANT INDUSTRIAL PROCESS ARCHETYPES AND THEIR RELEVANT CHARACTERISTICS

This section presents an overview of the process production in each industrial sector outlined in the previous section. For each sector, an archetype is defined, summarizing the most employed cooling demands and waste heat streams availability. Key characteristics are also discussed. While the processes analysed are not exhaustive, they aim to capture the main properties and temperature requirements of the most prevalent cooling demands within each sector.

4.1. FOOD AND DRINK PROCESS ARCHETYPE AND CHARACTERISTICS

The Food and Drink industry employ numerous processes requiring specific cooling to meet product requirements. In the meat industry, storage temperatures are generally kept below —2 °C to inhibit to growth of pathogens like Salmonella, Listeria, and Enterobacteriaceae. However, meat preparation processes may require even lower temperatures. For instance, freezing lines preserve meat at very low temperatures, ranging from –40 °C to –35°C. Fresh, unfrozen meat is typically kept at temperatures between –15 °C and –10 °C, while cured products, such as ham, are stored within –10 °C to 0 °C to achieve proper drying [42].

The dairy industry employs two primary cooling stages: one for storing raw milk and finished products, and another for producing dairy items like cream, cheese, and butter. Raw milk is stored in tanks at around 4°C to prevent spoilage, and final dairy products are maintained at 1°C to 4°C to retain flavour and quality. During processing, a critical cooling step occurs immediately after pasteurisation, where milk must be rapidly cooled to 4°C to prevent bacterial growth. In butter production, temperatures are maintained between 6°C and 10°C throughout most stages [43].

Regarding drinks sector, which accounts for 22% of the EU's food and drinks exports [2], wine, spirits, and beer have shown substantial growth in exports with an average increment of 10% from 2021 to 2022. This analysis considers wine and beer production as archetype processes within the industry. Winemaking consists of fundamental stages that vary by wine type [44] (see Figure 8). The initial steps involve destemming and crushing grapes to obtain the must, a mixture of skins, juice, seeds, and pulp, which requires cooling to preserve grape quality. For red wines, it must then undergo fermentation, while for white wines, it is pressed. During alcoholic fermentation, precise temperature control is essential: white wines typically require 18 °C to 20 °C, while red wines require 25 °C to 28 °C. After fermentation, red wines undergo malolactic fermentation, which generates little heat and thus demands minimal cooling. During the stabilisation process, wines are chilled from approximately 18 °C to -4 °C, a step that demands substantial energy. For instance, a winery located in La Rioja, Spain – a region with a long-standing tradition of winemaking – reported consuming approximately 500 kWh of energy during this step [45]. Finally, wine bottles are stored between 19 °C and 21 °C, which requires minimal cooling.

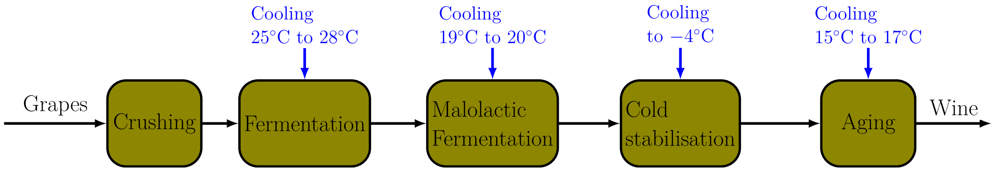


Figure 8 Simplified red wine production process.

Brewing is another key process in the Food and Drink industry shown in Figure 9. Brewing involves three main stages: the brewhouse, fermentation, and filling [46]. In the brewhouse, malted barley and cereals are ground and mashed with hot water at 75 °C. Sparge water at ambient temperature is then added to cool the mixture, which is subsequently transferred to a lauter tun to separate the wort. The wort is boiled to sterilise it and extract compounds from hops. After boiling, the hops and sediment are removed in a whirlpool. Cooling is crucial for the fermentation stage. The clarified wort from the whirlpool is cooled to approximately 14 °C to 18 °C for oxygenation before transferring to fermenters, where yeast is added. At this stage, the temperature is further reduced to around 7 °C. To complete maturation, the beer is cooled to −2 °C, a process that can last up to a week. Finally, the beer is diluted with a water-alcohol mixture in a mixer before packaging [47].

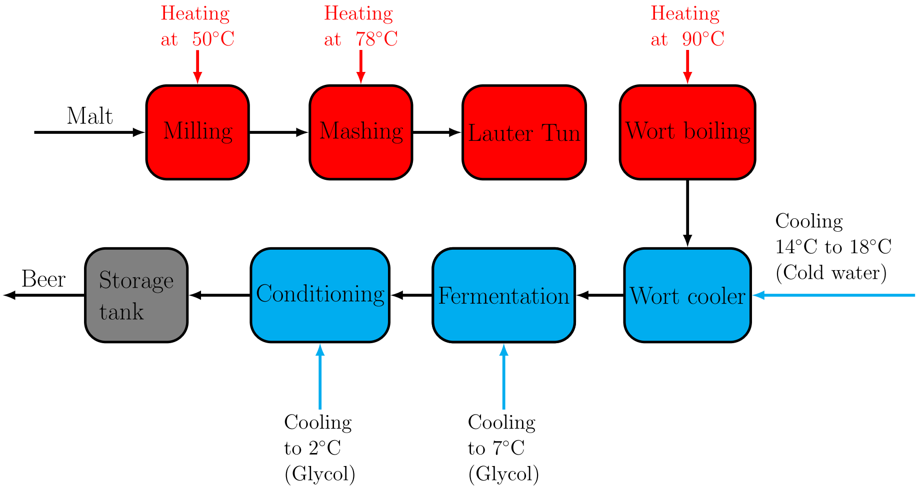


Figure 9 Simplified industrial brewing process.

4.2. PULP AND PAPER PROCESS ARCHETYPE AND CHARACTERISTICS

The Kraft process is the most widely adopted chemical pulping method, and the archetype in this deliverable is based on this process. A simplified diagram of the Kraft process is shown in Figure 10. The Kraft process begins with raw material preparation, where logs are converted into wood chips. These chips are then processed in a digester, where cellulosic fibres are separated to form pulp through treatment with “white liquor” – a chemical mixture of sodium hydroxide and sodium sulphide – at approximately 170 °C. This delignification step removes lignin from the wood. In subsequent stages, the fibres are washed, chemically bleached between 50 °C to 95 °C [48], drained, pressed, and dried.

A significant by-product of the delignification and washing stages is black liquor, which is processed in recovery boilers to produce steam. Before entering the boiler, black liquor is concentrated using multistage evaporators, from which soap is extracted as a by-product. Combustion of black liquor in the boiler generates a smelt, mainly composed of sodium carbonate and sodium sulphide. This smelt is collected at the bottom of the boiler, dissolved to form "green liquor," and then re-causticized with quicklime in a lime kiln, regenerating white liquor for reuse in the delignification stage and thereby closing the recovery loop.

The Kraft process requires two types of pre-treated water. The first type, treated water that is screened and demineralized, is used in processes involving direct contact with the pulp, such as pulp washing, bleaching, drying, and steam production. The second type, screened-only water, is primarily used for cooling, particularly in the chlorine dioxide plant, where it is maintained at 4 °C. Chlorine dioxide is the bleaching agent in this stage [49]. Treated water is utilized at various temperature levels: cold (4 °C in winter, 20 °C in summer), warm (~44 °C), and hot (50 °C to 70 °C).

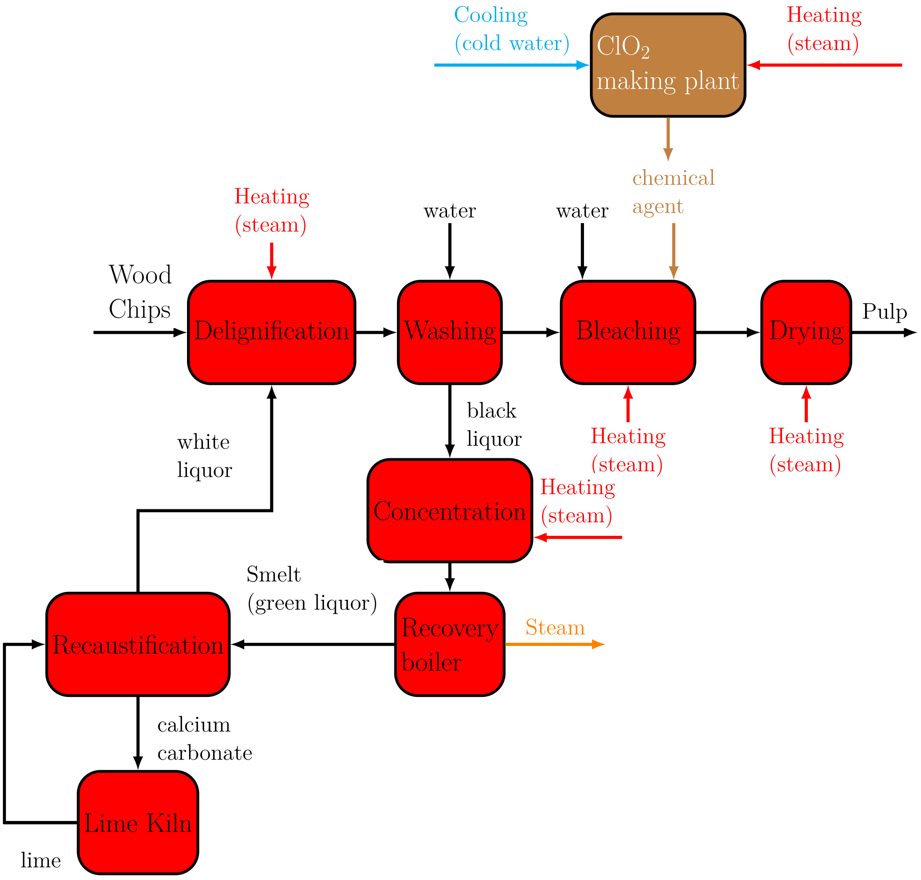


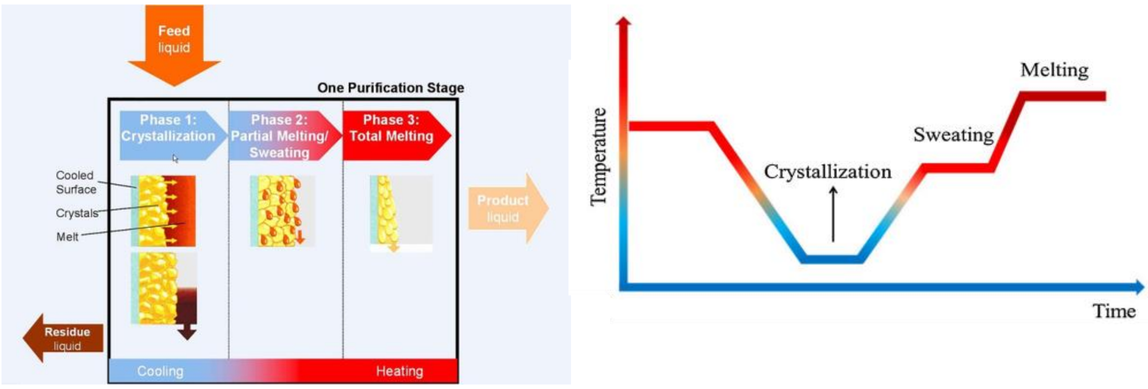
Figure 10 Simplified diagram of the kraft pulp making process.

4.3. PHARMA PROCESS ARCHETYPE AND CHARACTERISTICS

The pharmaceutical industry, apart from HVAC systems, relies on cooling for numerous processes, including melt crystallisation, ointment production, gelatine capsule moulding, and tablet formation. For example, key processes in tablet production include crystallisation and granulation. Crystallisation is used to separate organic compounds to achieve high purity. Some crystallisation processes require cooling to maintain specific temperatures, which vary based on the properties of the compounds being processed. For instance, ibuprofen crystallisation requires temperatures between 5 °C and 10 °C [50]. Another method, melt crystallisation, primarily uses heating energy but also depends on cooling to complete the final crystallisation stage [51]. Figure 11 illustrates the temperature profile for melt crystallisation.

Temperature management is crucial in tablet production to maintain product quality and meet regulatory standards, as each stage involves distinct heating and cooling requirements. Granulation, a critical step, modifies the properties of active pharmaceutical ingredients (APIs), such as low bulk density and poor flowability, to prepare them for compression [52]. This process typically involves heating the compounds to temperatures between 40 °C and 60 °C to bind powder particles [33], followed by cooling to restore the granules to room temperature [53]. During the subsequent drying stage, tablet mass temperatures are raised to 60 °C–80 °C to achieve the desired moisture content [34], while cooling ensures that temperatures remain below 30 °C during compression to protect heat-sensitive ingredients.

In the final coating stage, a coating material is applied to the tablet surface to achieve specific dosage properties. Heated air at 50 °C–70 °C is used to dry the coating, while exhaust air is cooled to 25 °C–30 °C to remove moisture and stabilize the tablets [54]. These temperature ranges vary depending on the formulation and manufacturing protocols. Cooling plays a vital role throughout the process, particularly during coating, where it ensures temperature control during film application and cools the tablets afterward, preventing thermal degradation and ensuring product integrity.



(a) (b)

Figure 11 Melt crystallization scheme (a) [55] and profile temperatures (b) [56].

Ointment production is another significant process that involves multiple heating, cooling and mixing stages. Cooling is crucial during homogenisation, which ensures the quality and stability of the ointment by aiding in the even distribution and dispersion of components at various stages. Heating and cooling cycles support the proper distribution and crystallisation of emulsifying waxes and stiffening agents around the solvent droplets and oil phases [57]. During production, petrolatum and waxes are melted, followed by the addition of other liquid ingredients. Cooling is applied to bring the ointment to room temperature before it is filled into containers, such as jars or tubes. For topical ointment formulations, cooling steps are typically conducted between 75°C and 43°C and from 43°C to 32°C, as illustrated in Figure 12.

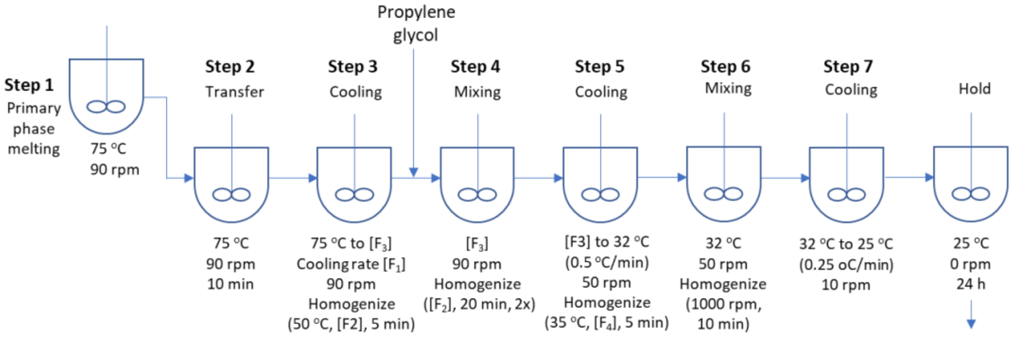


Figure 12 Flow diagram of ointment process reported in [57].

The cooling rate in ointment production process is adjusted to either accelerate or delay the cooling process, depending on the requirements of the manufacturing stage. For example, the cooling speed is regulated within a range of -50 °C to -7.5 °C at different stages of the process [58]. This precise control of the cooling process is achieved by circulating water through jackets around the vessels [59].

4.4. BIOFUEL PROCESS ARCHETYPE AND CHARACTERISTICS

Biofuel production involves multiple steps, with variations primarily depending on the type of raw material and catalyst used. Biofuel can be derived from various oils, including vegetable oils, animal fats, tallow, and recycled waste oils. The choice of oil significantly affects the quality of the final product. Catalyst selection also varies: potassium hydroxide is typically used for ethyl ester production, while potassium and sodium hydroxides are used for methyl esters, depending on process specifications. The biofuel production process begins with the mixing of methanol and the catalyst, alongside the pre-treatment oil (see Figure 13). During pre-treatment, the oil is heated to approximately 35 °C to reduce its viscosity, making it suitable for subsequent stages. This step also removes contaminants and ensures an appropriate oil composition. The next stage is esterification, where any free fatty acids present in the oil are converted into esters, which reduces free fatty acid content and prevents soap formation in subsequent transesterification. This reaction typically occurs at temperatures between 50 °C to 60 °C, with cooling applied for condensation. Esterification lasts from 4 to 16 hours [60].

Transesterification is the core step in biofuel production, where oil reacts with alcohol to produce esters and glycerol. During this process, triglycerides (oil) are sequentially converted into diglycerides, monoglycerides, and finally into fatty acid methyl esters (FAME), which form the biofuel, with glycerol as a by-product [61]. The process operates between 45 °C and 65 °C, and cooling is required to manage condensation. An excess of methanol, typically at a 1:2 ratio above the stoichiometric amount, ensures a more complete reaction and a higher-quality biofuel. After transesterification, distillation is used to separate the biofuel from glycerol. This step requires precise temperature control, with biofuel heated to a range of 210 °C to 250 °C [62]. Methanol recovery occurs at two stages in the process through vacuum distillation, where methanol vapor (boiling point 64.7 °C) is condensed and reclaimed. Cooling is applied here to facilitate condensation. The final stages involve washing and drying to improve biofuel purity by removing residual impurities such as soap and water [63]. Warm water is used to absorb methanol and release impurities.

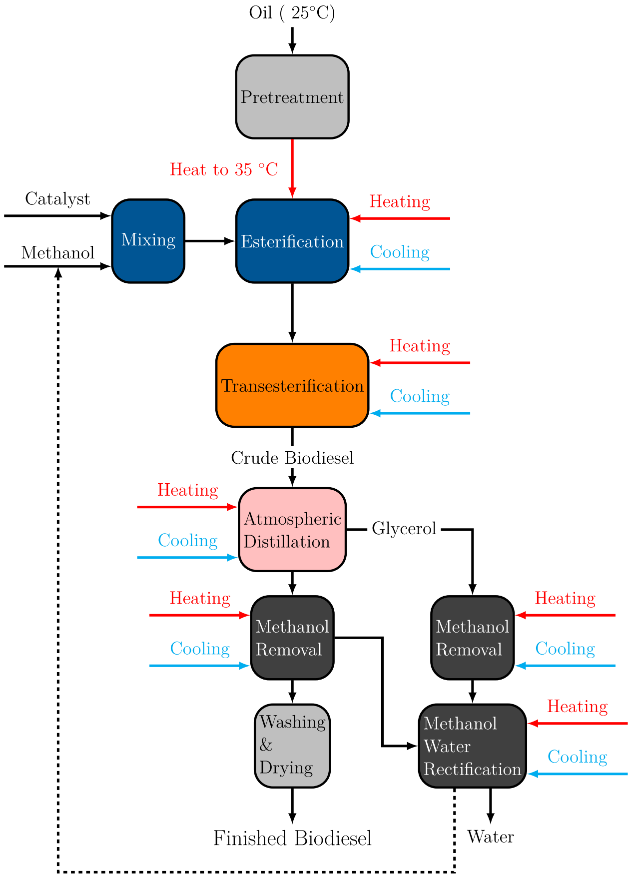


Figure 13 Flow diagram of the bio-fuel production process.

As observed, the biofuel production process involves a series of reactions where condensation is essential. Reliable cooling systems are required to provide sufficient cooling to condense separated compounds in each stage. The primary cooling technologies in the biofuel industry include cooling towers [40] and chillers, which provide cooling to coils used in vacuum distillation systems.

5. RE-WITCH TECHNOLOGY BASIC REQUIREMENTS

5.1. ADSORPTION RE-WITCH TECHNOLOGY

The RE-WITCH project focuses on advancing adsorption cooling technology by building upon an innovative prototype design currently validated at Technology Readiness Level 5 (TRL 5). The adsorption chiller leverages the capacity of solid sorbent materials to adsorb and desorb water vapour, utilising low-grade waste or renewable heat to drive the cooling process. This innovative approach eliminates the need for mechanical compressors, making it an energy-efficient and sustainable solution for industrial cooling applications.

Key technical targets to be achieved by the RE-WITCH adsorption chiller:

- **Driving Temperature:** Operates effectively with driving heat at temperatures as low as 60 °C.

- **Thermal COP :** Targeted at 0.65.
- **Electric COP:** Targeted at >20, significantly reducing electricity requirements compared to conventional systems.
- **Compactness:** Expected to achieve >17 kW/m^3 cooling power density.

5.2. ABSORPTION RE-WITCH TECHNOLOGY

Absorption cooling is a thermally driven cooling technology that replaces the mechanical compressor in conventional vapour-compression cycles with a thermochemical process. Utilizing low-grade waste heat or renewable energy sources (e.g., solar), absorption chillers provide an environmentally friendly alternative for refrigeration and cooling.

At the heart of the technology lies a sorbent-refrigerant working pair, commonly lithium bromide (LiBr) and water, that enables the refrigeration cycle. These systems typically consist of key components such as a generator, condenser, evaporator, and absorber, working within specific temperature constraints. For instance, the operational parameters are characterized by low driving heat temperatures, generally ranging from 70 °C to 100 °C, and chilled water outlet temperatures, which are typically between 3 °C and 10 °C. Conventional absorption chillers usually exhibit a COP ranging from 0.6 to 0.8 for cooling purposes.

Nevertheless, despite their merits, traditional absorption chillers encounter intrinsic limitations associated with the risks of crystallization in the LiBr-water system, as well as restrictions on driving and cooling temperatures. During the development of RE-WITCH these obstacles will be addressed through the implementation of two novel technologies: hybrid absorption chillers and dual evaporator/absorber chillers, which aim to improve the adaptability, efficiency, and utility of absorption cooling systems in industrial contexts.

2.2.1 HYBRID ABSORPTION CHILLER DESIGN

The hybrid absorption chiller technology, which will be developed within the framework of RE-WITCH, integrates a mechanical vapour compressor in the absorption cycle, between the evaporator and the absorber. This hybridization significantly enhances system performance by leveraging the advantageous characteristics of both absorption and compression cycles.

In conventional absorption chillers, the pressure levels within the absorber are constrained by the crystallization threshold of the LiBr solution, thereby constraining the temperature lift (defined as the differential between the chilled water and the reject heat temperatures). The hybrid system effectively mitigates this constraint by employing the mechanical compressor to elevate the absorber pressure, consequently facilitating elevated reject heat temperatures without incurring the risks of crystallization.

Key technical targets to be achieved by the RE-WITCH hybrid absorption chiller:

- **Driving Heat Temperature:** ~80–120 °C
- **Chilled Water Temperature:** 3–5 °C
- **Reject Heat Temperature:** Up to 60 °C
- **Thermal Cooling COP:** 0.65–0.70

- **Electric Cooling COP:** Up to 9
- **Electric Heating COP:** Up to 23

2.2.2 DUAL EVAPORATOR/ABSORBER CHILLER DESIGN

The dual evaporator/absorber technology incorporated within RE-WITCH presents a groundbreaking configuration featuring two evaporator-absorber pairs. This architecture facilitates simultaneous cooling at two distinct temperature levels (for instance, 10 °C and 20 °C), rendering it appropriate for industrial applications that demand variable cooling requirements.

The strength of this configuration lies in the flexibility obtained by allowing each pair of absorbers and evaporators to operate independently, resulting in the elimination of the series flow configuration observed in conventional dual evaporator configurations. This parallel configuration reduces crystallization risks and optimizes the utilization of heat transfer surfaces.

Key technical targets to be achieved by the RE-WITCH dual evaporator/absorber chiller:

- **Driving Heat Temperature:** 80–110 °C
- **Chilled Water Temperatures:** 10 °C and 20 °C
- **Thermal Cooling COP:** ~0.7
- **Cooling Capacities:** ranging from 40 kW up to 400 kW per unit

5.3. PRELIMINARY INTEGRATION SUGGESTIONS OF RE-WITCH TECHNOLOGIES IN REFERENCE INDUSTRIAL PLANTS

In the following, some examples of possible integration approaches for the RE-WITCH technologies inside reference industrial plants are reported. This preliminary analysis is conceived to define some boundaries under which, within Task 4.2 and Task 4.3, whose results will be summarized in D4.2, the detailed RE-WITCH integration routes will be reported.

2.2.3 PULP AND PAPER INDUSTRY

Recommended RE-WITCH Technology: Adsorption Chiller

The Pulp & Paper industry generates significant low-grade waste heat from processes like digesters, multi-effect evaporators, and air compressors (if any). Adsorption chillers are highly suitable here due to their ability to operate efficiently on low-grade waste heat (e.g., <90 °C), aligning perfectly with the industry’s waste heat characteristics.

The containerized design offers flexibility for integrating adsorption chillers near specific waste heat sources like evaporators or recovery boilers, reducing distribution losses. Furthermore, adsorption chillers can meet the industry’s primary cooling demands such as:

- Cooling for conditioned spaces and equipment.
- Stabilizing chemicals (e.g., chlorine dioxide, ClO_2, in bleaching).

By recovering low-grade heat, this solution enhances energy efficiency and provides eco-friendly cooling without relying heavily on external electricity or refrigeration systems.

2.2.1 BREWERY INDUSTRY

Recommended RE-WITCH Technology: Adsorption Chiller

The brewery industry produces substantial low-temperature waste heat during boiling (in the Kettle/Copper), wort cooling, and from the hot liquor tank. Adsorption chillers can efficiently utilize this heat to meet the cooling demand for the fermentation and conditioning stages.

Key integration benefits include:

- Utilizing heat recovered from boiling (~101 °C) and the hot liquor tank to power adsorption chillers.
- Producing chilled water for wort cooling and fermentation, reducing dependency on external cooling systems.
- Storing waste heat for use in future brewing cycles, improving overall thermal efficiency.

Adsorption chillers are an ideal match due to their compatibility with low-temperature waste heat and their ability to support sustainable brewing practices.

2.2.2 PHARMACEUTICAL INDUSTRY (OINTMENT MANUFACTURING)

Recommended RE-WITCH Technology: Adsorption Chiller

The ointment manufacturing process involves significant cooling requirements, particularly during the cooling and homogenization step, where temperatures need to be reduced from 70 °C to 30–35 °C. Adsorption chillers are ideal due to their ability to utilize low-grade waste heat (e.g., from boilers or heated liquid phases) to provide cooling without reliance on high electricity consumption.

Key integration benefits include:

- Waste heat from boilers and hot liquid phases can be effectively utilised for cooling, reducing the need for additional energy input.
- Producing chilled water that can be used for both process, equipment and building cooling using low-grade waste heat.

2.2.3 BIOFUEL INDUSTRY (BIODIESEL PRODUCTION)

Recommended RE-WITCH Technologies: Hybrid Absorption Chiller and Dual Evaporator/Absorber Absorption Chiller

Hybrid Absorption Chiller:

The idea of using a hybrid absorption chiller seems ideal for integrating with processes such as methanol recovery (or drying process) and glycerol purification, where both heating (60–70 °C) and cooling (20–30 °C) are required. The hybrid absorption chiller can simultaneously deliver cooling and heating, leveraging the waste heat from methanol drying, and transesterification, and providing cooling and heating to the washing and drying process respectively, to maximise efficiency.

Dual Evaporator/Absorber Absorption Chiller:

The biodiesel production process involves several stages where low-to-moderate temperature waste heat (50–100 °C) is available, such as methanol recovery, transesterification, and biodiesel drying. A dual evaporator/absorber absorption chiller is ideal for this application due to its ability to handle multiple cooling demands simultaneously and optimize energy usage. For instance, this technology can provide cooling at the phase separation and washing stage simultaneously.

In conclusion, the integration of RE-WITCH technologies across the selected reference cases (i.e. Pulp & Paper, brewery, pharmaceutical, and biofuel) demonstrates significant potential for enhancing energy efficiency, reducing operational costs, and contributing to sustainable industrial practices. Each sector exhibits distinct opportunities for waste heat recovery and utilization, from capturing low-grade heat in brewing and cooling operations to reclaiming high-temperature waste heat from boilers and reactors in pharmaceutical and biodiesel processes. Coupling these waste heat recovery systems with RE-WITCH technologies can result in sustainable process cooling in industries. Table 4 shows a summary of available waste heat temperature sources, required heating and cooling conditions and appropriate RE-WITCH technology proposed for each industrial sector type.

Table 4: Summary of Industrial sectors along with proposed RE-WITCH technologies.

S.No	Industry	Available waste heat temperatures	Required Heating and Cooling conditions	RE-WITCH technology
1	Pulp & Paper Industry	• Digester: (~140 °C) • Recovery boiler (~450-500 °C) • Flue gases from dryer (~80-100 °C)	• Equipment and/or conditioned space cooling (~20-25 °C)	• Adsorption Chiller
2	Brewery Industry	• Hot Liquor Tank (~150-180 °C) • Kettle or Copper (~101 °C) • Wort (~60-70 °C)	• Wort Cooling (~30 °C) • Fermentation (~8-20 °C)	• Adsorption Chiller
3	Pharma Industry (Ointment manufacturing)	• Flue gases from ingredient Preparation (~70-80 °C)	• Homogenization (~30-35 °C)	• Adsorption Chiller
4	Biofuel Industry (Biodiesel production)	• Pretreatment of feedstock (~60-80 °C) • Esterification (~50-70 °C) • Transesterification	• Drying (~60-90 °C) • Washing (~20-30 °C)	• Hybrid absorption chiller

		(~60-65 °C) • Glycol purification (~70-100 °C) • Methanol recovery (~60-70 °C) • Drying (~60-90 °C)	• Phase separation (~40-60 °C) • Washing (~20-30 °C)	• Dual evaporator/ absorber absorption chiller

6.4 PRELIMINARY ASSESSMENT OF INDUSTRIAL PROCESSES AND INDUSTRIES WITH A PROPER MATCH OF WASTE HEAT TEMPERATURE AND COOLING DEMAND

To evaluate the compatibility between industrial heat sources and cooling demands, it is essential to identify processes and sectors that can be optimised through waste heat recovery. This involves assessing the mutual presence of significant waste heat sources and cooling processes, considering the waste heat temperatures manageable by RE-WITCH technologies. An initial assessment, based on literature and market data [64–68], is presented in Table 5.

Table 5 Potential cooling uses by industrial sector.

WH recovery		WH Temperature [°C]	Potential cooling uses and temperature[1]:
Industrial sector	**Process source**		
Food, plastic and chemicals	Cooling water from refrigeration condenser	30-40	CPS, DC, RFS
Plastic, papers, wood, textile	Cooling water from refrigeration of compressors	30 - 50	CPS, DC, CWT
Chemical, wood	Hot processes (thermoforming, bonding)	30 - 230	CPS, DC
All sectors	Cooling water from CHP engines or from electric engines of actuators/specific processes	70 - 120	CPS, DC, RFS
Food, wood	Cooling water from process ovens	70 - 230	CPS, DC, RFS
All sectors	Exhausts from boilers	70 - 120	CPS, DC, RFS, CWT

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[1] Limited to temperatures achievable by RE-WITCH, not looking at refrigeration/freezing for temperature <-10 °C for example

Textile, Chemicals, plastic	Low pressure steam and condenser heat	40 - 150	CPS, DC

Note: The meaning of the abbreviation of the potential uses and their temperatures are: Cooling process and spaces (CPS): 4 – 10 °C, Deep cooling (DC): −10 – 4 °C, Refrigeration for food storage (RFS): −10 °C, Cooling for water in water treatment in textile (CWT): 10°C.

Starting from this preliminary assessment, it has been also analyzed which could be the WH sources to be more effectively valorized by different state-of-the-art sorption cooling technologies. The aim was to clarify which might be the best thermal COP achievable considering both waste heat temperatures and cooling temperatures. The results are represented in Table 6.

Table 6 Expected COP values of RE-WITCH technologies.

TAT analysed **ADC = Adsorption chiller** **ABC = Absorption chiller**	**Cooling output temperature from the heat-to-cold system [°C]**		
Waste Heat:	**T1**$_f$: −10 – 0	**T2**$_f$: 0 – 4	**T3**$_f$: 4 – 10
T_1: 30 – 60 [°C]	ADC COP ≈ 0,12 – 0,20	ADC COP ≈ 0,15 - 0,25	ADC COP ≈ 0,25 - 0,40
T_2: 60 – 90 [°C]	ABC COP ≈ 0,50 - 0,55	ABC COP ≈ 0,60 - 0,64	ABC COP ≈ 0,64 - 0,70 ADC COP ≈ 0,30 - 0,40
T_3: 90 – 120 [°C]			ABC COP ≈ 0,70 - 0,74

6. CONCLUSIONS

Overall, this deliverable presents a comprehensive analysis of cooling requirements across key industrial sectors and evaluates the integration potential of RE-WITCH technologies. The findings underscore the viability of utilising advance adsorption and absorption cooling technologies to enhance energy efficiency, reduce operational costs, and promote sustainable industrial practices.

The deliverable identifies critical cooling needs and waste heat characteristics in four industrial sectors: Food and Drink, Pulp & Paper, Pharmaceutical and Biofuel. These sectors represent a diverse array of processes and temperature requirements, ranging from low temperatures in food preservation to moderate cooling in biodiesel production. Detailed archetypes of industrial process reveal the high variability and energy intensity of cooling demands, highlighting the opportunities for waste heat recovery and reuse through RE-WITCH technologies.

The RE-WITCH adsorption technology demonstrates suitability for industries with significant low-grade waste heat availability, such as the Pulp & Paper and some Food and Drink processes such as Brewery production. Its ability to operate efficiently with waste heat temperatures below 90 °C makes it particularly advantageous for these applications. Similarly, hybrid and dual evaporator/absorber absorption chillers are highly adaptable to the Bio-fuel and Pharmaceutical industries, offering flexible cooling solutions that address multiple temperature demands.

Key integration strategies proposed in this report include utilising adsorption chillers for wort cooling in breweries and chemical stabilisation in pulp production, as well as hybrid adsorption chillers for biodiesel methanol recovery and dual evaporator chillers for simultaneous cooling in sources, aligning with the project's objectives to maximise waste heat utilisation and reduce reliance on external energy sources.

In conclusion, the integration of RE-WITCH technologies into industrial cooling systems presents a crucial opportunity to achieve energy efficiency and sustainability. By aligning innovative cooling solutions with sector needs.

There is very little data available on sources of cooling demand for Pharmaceutical and Biofuel sector industry. However, the few found references provided information about the temperature levels of heating and cooling demand to give.

The performed analysis will be exploited in the following activities belonging to WP4 as well as to support modelling and replication analyses in WP5 and WP17 respectively.

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