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Review

Decarbonizing European Industry: A Novel Technology to Heat Supply Using Waste and Renewable Energy

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Abstract: This study examines the potential for the smart integration of waste and renewable energy sources to supply industrial heat at temperatures between 150 °C and 250 °C, aiming to decarbonize heat demand in European industry. This work is part of a European project (SUSHEAT) which focuses on developing a novel technology that integrates several innovative components: a Stirling cycle high-temperature heat pump (HTHP), a bio-inspired phase change material (PCM) thermal energy storage (TES) system, and a control and integration twin (CIT) system based on smart decision-making algorithms. The objective is to develop highly efficient industrial heat upgrading systems for industrial applications using renewable energy sources and waste heat recovery. To achieve this, the specific heat requirements of different European industries were analyzed. The findings indicate that industrial sectors such as food and beverages, plastics, desalination, textiles, ceramics, pulp and paper, wood products, canned food, agricultural products, mining, and chemicals, typically require process heat at temperatures below 250 °C under conditions well within the range of the SUSHEAT system. Moreover, two case studies, namely the Pelagia and Mandrekas companies, were conducted to validate the effectiveness of the system. An analysis of the annual European heat demand by sector and temperature demonstrated that the theoretical potential heat demand that could be met by the SUSHEAT system is 134.92 TWh annually. Furthermore, an environmental impact assessment estimated an annual significant reduction of 19.40 million tonnes of CO_2 emissions. These findings underscore the significant potential of the SUSHEAT system to contribute to the decarbonization of European industry by efficiently meeting heat demand and substantially reducing carbon emissions.

Keywords: decarbonization; heat demand; high-temperature heat pumps; PCM-TES system; SUSHEAT

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1. Introduction

Decarbonizing industrial production is crucial to achieving the European Union's climate change targets. This involves drastically reducing energy consumption and CO_2 emissions and switching to renewable energy sources (RES) [1]. Furthermore, rising energy costs, relying on fossil fuels due to the global crisis, and increasing energy demand to reduce the carbon footprints of products are motivating companies worldwide to develop strategies to decarbonize process heat [2]. In recent years, the European Union (EU) underwent significant changes, with the transition from EU28, which included the United Kingdom, to EU27 following Brexit in 2020, impacting various policies and strategies, particularly in the areas of energy and industrial decarbonization. In the EU, roughly two-thirds of greenhouse gas emissions within the industrial sector are attributed to the utilization of fossil fuels to generate heat and electricity. The chemical, petrochemical, and non-metallic minerals industries are regarded as the largest consumers of energy, followed by the paper, pulp and printing, food, and steel industries [3]. Overall, energy production in all its forms is responsible for more than 70% of total greenhouse gas (GHG) emissions as depicted in Figure 1. As a result, the main contributors to GHG emissions in 2022 are related to the energy supply (26.60%), domestic transportation (23.10%), industry (19.60%), residential and commercial (11.50%), and agriculture (8.23%) [4]. An increase in energy consumption directly correlates with higher emissions, illustrating the close relationship between energy consumption and emissions [5]. Final energy consumption (FEC) includes all the energy provided to the different industrial sectors and serves as a measure of consumption at the FEC point [6]. The aforementioned five sectors account for around two-thirds of the total energy consumption in the industrial sector [7], mainly in the form of heat and electricity. The majority of the remaining energy consumption is related to heat generated from fuels (such as oil coal, and gas), renewables (such as biomass), and also combined heat and power (CHP) systems [8]. This includes both heating for spaces and heating for industrial processes. Odyssee-Mure data reveal that electricity constitutes roughly 30% of industrial energy consumption in the EU. Of this, 70% is allocated to heating, with temperatures exceeding 1000 °C in metal processing [9]. Figure 2 also illustrates an examination of final energy consumption by end-use in the EU27 in the year 2022, showing three main categories: transport (31%), households (27%), and the industry sector (25%) (see Figure 2). It should be noted that international aviation and marine bunkers are not included in the transport category [10].

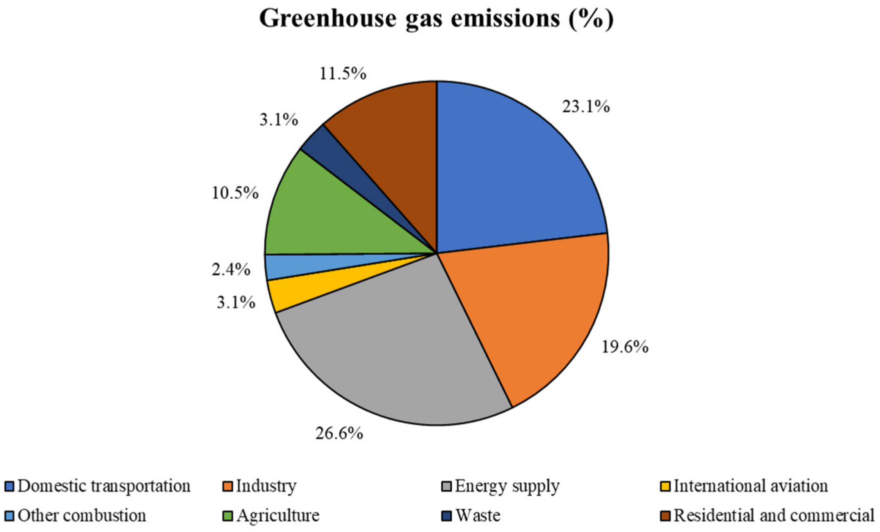

Figure 1. Greenhouse gas emissions by sector in EU27 for 2020 [4].

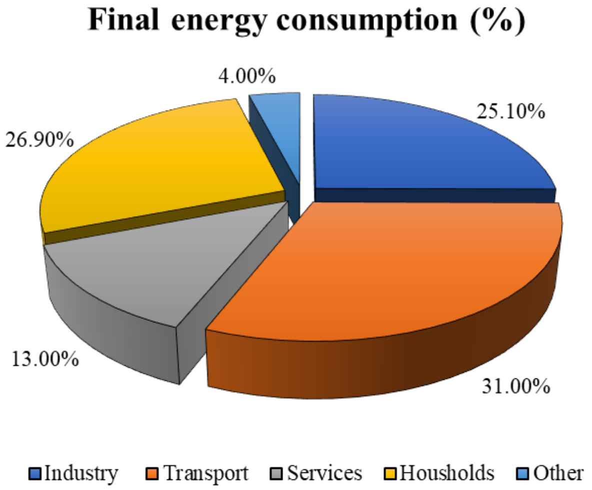

Figure 2. Breakdown of final energy consumption by sector within the EU27 for the year 2022, represented as a percentage of the overall energy consumption, based on terajoules [10].

However, the decarbonization alternatives leading the industrial transition include improving process efficiency and implementing novel processes to reduce end-use energy consumption, using waste heat, and switching from fossil fuels to renewable energy sources and raw materials [11]. Conventionally, industrial processes and operations requiring high-temperature heating (HTH) ranging between 100 and 125 °C have been provided by low-pressure steam boilers, commonly fueled by fossil fuel energies or electrical heating systems that are not environmentally friendly [12]. Nevertheless, many industrial processes produce excess waste heat as a by-product, which is either free or requires cooling tower operation to dissipate it into the environment. This waste heat can be found at low temperatures and cannot be effectively reused in other processes in industries. In the recent European energy framework, utilizing recovered industrial waste heat (IWH) supplies a suitable opportunity to replace primary energy consumption with a cost-effective, low-emission energy source [13]. Numerous studies are available that investigated the potential of industrial waste heat from perspectives related to energy efficiency and policy perspective [14,15]. The primary objective of these types of studies is to assess the recoverable waste heat and explore its possible applications. Sectors such as steel [16] and food [17] are examined for heat recovery, with proposals for technologies such as ORC for heat-to-power conversion [18] and heat pumps for intensification [19]. The field of research is dynamic due to the wide range of possibilities for waste heat utilization. However, concerning industrial waste heat, this potential is not only extensively unexplored but also unacknowledged. To promote the widespread adoption of recovered IWH, comprehensive assessments with extensive scope and detailed spatial resolution are essential. The optimal approach is to reuse this waste heat within the originating process, thereby avoiding scenarios where past investment decisions prevent additional energy efficiency improvements.

Furthermore, when high-temperature heat demand coincides with the availability of nearby low-temperature waste heat, it presents an opportunity to utilize heat pumps. These devices are among the technologies that exist to recover industrial waste heat, enabling energy integration and improving the overall system efficiency [12]. Hence, with the rising share of electricity being generated from renewable sources, the use of an electric-powered industrial heat pump is a robust option for a more sustainable industrial sector. Technologically, heat pump prototypes currently under development can achieve temperatures of up to 200 °C and beyond [2]. Several research efforts are also focused on developing high-temperature heat pumps (HTHPs) capable of operating with sink temperatures ranging from 160 °C to 200 °C [20,21], although their market implementation is expected to take several years. Enerin offers HTHPs utilizing helium (R704) as the working fluid and employing double-acting piston compressors within a Stirling cycle. This configuration enables adaptable operating conditions, high lifting capabilities, and the delivery of temperatures exceeding 200 °C [22]. Furthermore, Olvondo Technology's High-Lift HTHP system, implemented in the heat pumps at AstraZeneca in Sweden, was designed to operate within this temperature range [23]. Wolf and Bles [24] assessed the potential applications of heat pumps by considering 15% of the overall industrial energy consumption in Europe.

Nonetheless, the lack of progress in developing products for higher temperatures is often due to inadequate comprehension by manufacturers of heat pumps for applications of industrial processes, and market demand. To address these constraints, the EU funded the SUSHEAT project, whose main objective is to design a hybrid renewable heat upgrade system that aims to replace fossil fuel-based boilers in the European industrial landscape through three novel technologies: an advanced Stirling cycle-based HTHP capable of temperatures up to 250 °C, a bio-inspired phase change materials (PCM) TES system and a control and integration twin (CIT) system. Therefore, this study explores the potential application of the concept of the European SUSHEAT project to meet the industrial heat demand within the European industry. Section 2 introduces the SUSHEAT concept. Section 3 outlines energy consumption, heat demand, and industrial processes in the EU. Section 4 covers the Theoretical Potential (TP) of implementing the SUSHEAT system in the EU28. Section 5 focuses on waste heat in industries and heat pumps while Section 6 represents the environmental advantages of applying the SUSHEAT system in the EU 28. Lastly, Section 7 presents the conclusions of this study.

2. The SUSHEAT Concept

SUSHEAT incorporates several novel technologies such as an HTHP, a PCM bio-inspired TES system, and a CIT system for advanced heat upgrading in leading laboratories [25]. Moreover, SUSHEAT effectively assesses the best integration of heat upgrading systems, incorporating key enabling components and leveraging off-the-shelf renewable energy systems, such as solar Fresnel collectors, to enhance feasibility even at low temperatures. On the other hand, the integration depends on harvesting energy from waste heat, utilizing a linear Fresnel collector (LFC), and using ambient heat as a reservoir.

Figure 3 shows the four main components that integrate the SUSHEAT system. These main components are detailed as follows:

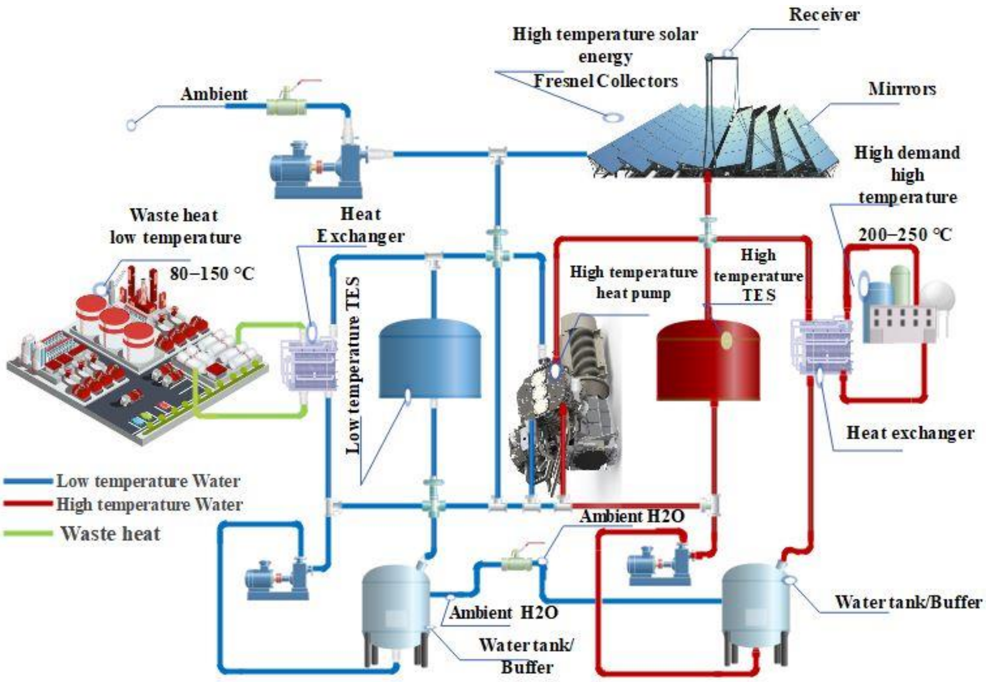

Figure 3. The SUSHEAT system in this study.

(1) High-temperature heat pump: It should be noted that low-temperature heat sources, such as waste heat, cooling water, or ambient heat are upgraded via the HTHP, which employs helium and innovative Stirling technology. This process generates high-temperature heat, ranging from 150–250 °C, needed for industrial applications like drying, distillation, or rapid heating in the SUSHEAT case studies. Utilizing both waste heat and electrical energy, a heat pump produces steam at temperatures up to 250 °C and pressures up to 45 bar. This setup can realistically achieve a coefficient of performance for heating (COP) ranging from 1.9 to 2.8. The peak efficiency of Stirling cycle heat pumps [25], is 32% of the Carnot cooling coefficient of performance (COP). However, ENER's calculations suggest that achieving up to 50% of the Carnot cooling COP is possible. The 2022 model of ENER's heat pump is projected to reach the peak Carnot fraction at a temperature ratio of 1.7 K/K—specifically, a 250 °C sink and a 35 °C source. Notably, the actual COP tends to be higher with smaller temperature differences, making it essential for R&D to focus on extending the Carnot fraction to lower temperature ratios to enhance the COP further. The highest reported COP at a 1.26 K/K ratio (with a 105 °C sink and a 26 °C source) is 2.2, representing 32% of the Carnot cooling COP. ENER's heat pump used in this project is anticipated to achieve 42%, equating to a COP of 2.8 at 1.26 K/K, which could also be reached with a 250 °C sink and a 142 °C source once the seals are finalized. However, we observe different COP values

(ranging from 1.9 to 2.8) depending on the temperature ratios for the case studies, operating within different temperature ranges. With future enhancements, this efficiency could rise to 50%, resulting in a COP of 2.9 at those temperatures.

(2) Thermal Energy Storage: The advanced TES system provides reliable, flexible, and adaptable heat supply, completely independent of waste heat recovery and renewable availability. Technological improvements are being made for novel latent heat TES. In the SUSHEAT system, there are two TES systems: one for storing waste energy at a low temperature for later upgrading, and another for storing heat at a high temperature for use as needed by the industrial process. The optimal PCM is being researched and selected for the SUSHEAT hybrid renewable heat upgrade system. This system is designed to capture and store surplus thermal energy in peak solar periods and then provide it to processes as needed. Low-temperature TES is typically in the range of 70–85 °C, whereas high-temperature TES operates between 180–200 °C. The proposed bio-inspired TES maximizes power density by overcoming the heat transfer limitations of traditional PCM-based TES designs, which are typically hindered by the low thermal conductivity of PCM.

(3) Linear Fresnel Collectors: SUSHEAT employs commercially available linear Fresnel collectors (LFC), which use linear Fresnel mirrors for solar concentration. The system features an elevated receiver at the focal point of the mirrors, allowing the mirrors to capture and concentrate solar irradiance onto the considered receiver. Here, a heat transfer fluid (HTF) absorbs the given heat, reaching temperatures of up to 185 °C. It is important to note that it is capable of supplying heat to both high and low temperatures areas. This heat is then transferred to the PCM storage system and various processes. The SUSHEAT system facilitates the extended integration of renewable energy to harvest energy from waste heat, ambient as a heat reservoir, and support industrial LFC operations within the temperature range of 150–250 °C.

(4) Control and Integration Twin: The concept is complemented by a control system that coordinates all the components and determines the optimal energy source and amounts needed to charge the two thermal storage systems, taking into account resource availability and the energy needs of the industry and constraints. The CIT system offers user-friendly tools and a digital twin for control and guidance, supported by smart decision-making algorithms. The SUSHEAT CIT system uses an operational 3D digital twin for experimental simulations and an AI-guided control system. This practice enables research in three main directions: (i) developing prototypes for our case studies, (ii) enhancing the adaptability of the solution across various industries, and (iii) visualizing process-oriented changes in near real-time. This optimizes and improves energy management for processes in Industry 5.0.

3. Energy Consumption, Heat Demand, and Industrial Processes in the EU

3.1. Final Energy Consumption (FEC)

Figure 4 displays the FEC of the SPIRE and non-SPIRE industries by the industrial sector at the EU27 level for the year 2022. In 2022, the EU final energy consumption was 37,771 PJ, a decrease of 3.9% compared to 2021. From 1994 onwards, FEC gradually increased, reaching a peak of 41,447 PJ in 2006. By 2022, FEC declined by 8.9% from its peak. The chemical and petrochemical industry emerged as the leading consumer, accounting for 1892 PJ, or 20.0% of the overall FEC in the EU's industrial sector in 2022. It is closely followed by the non-metallic mineral industry with 1367 PJ (14.50%) and the pulp, paper, and printing industry with 1279 PJ (13.5%). Other sectors exceeding the 10% mark include food, beverages, and also tobacco (1156 PJ or 12.2%) as well as iron and steel (962.0 PJ or 10.2%) (see Figure 4) [10].

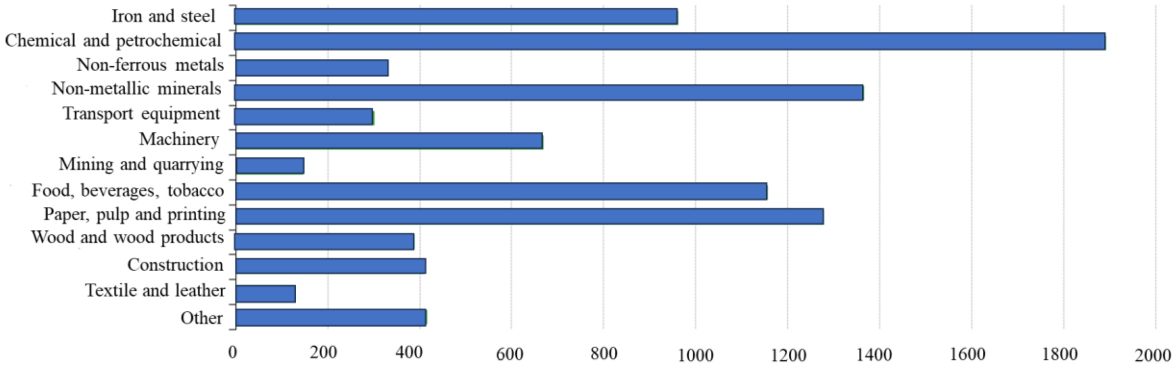

Figure 4. Final energy consumption (PJ) in the industry sectors within EU27 in 2022 [10].

3.2. Heat Demand

This section used data from Papapetrou et al. [7] and the European Commission [26] to analyze the FEC and overall heat demand of the industrial sector in 2015, which were then used to calculate the industrial heat demand for the countries in the EU28. However, the contribution of the heat demand for each country in the EU28 for 2015 is shown in Figure 5 while a breakdown of the heat demand by the industrial sector is demonstrated in Figure 6. The total heat demand for the EU28 amounted to 1600 TWh. Figure 5 shows that a significant part of this demand came from Germany (22%), followed by France (10.4%), Italy (10.1%), the United Kingdom (UK) (8%), and Spain (7.8%), with the remaining countries contributing significantly lower percentages.

Concerning the heat demand in each industrial sector, Figure 6 illustrates that the chemical and petrochemical sector recorded the highest demand at 328.8 TWh, followed by iron and steel (289.2 TWh), non-metallic minerals with a value of 279.4 TWh, and food and beverages along with a value of 208.9 TWh. Subsequently, this was followed by lower demand for paper, pulp, and printing (106.3 TWh), machinery (95.4 TWh), non-ferrous metals (84.6 TWh), unspecified industries (82.8 TWh), and construction (63 TWh) (see Figure 6).

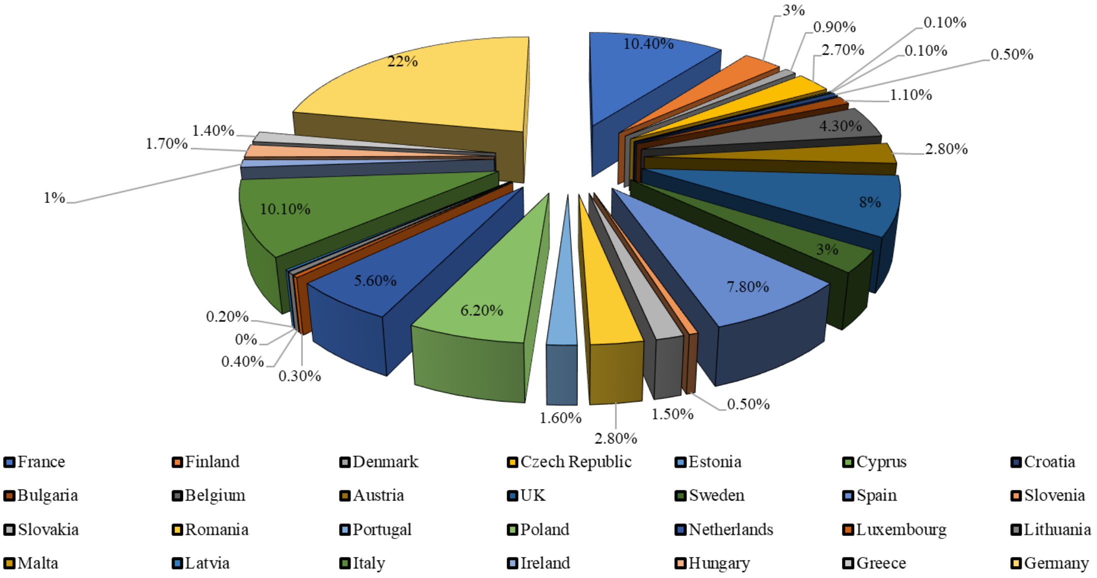

Figure 5. Heat demand breakdown by EU28 country (%) [7,26].

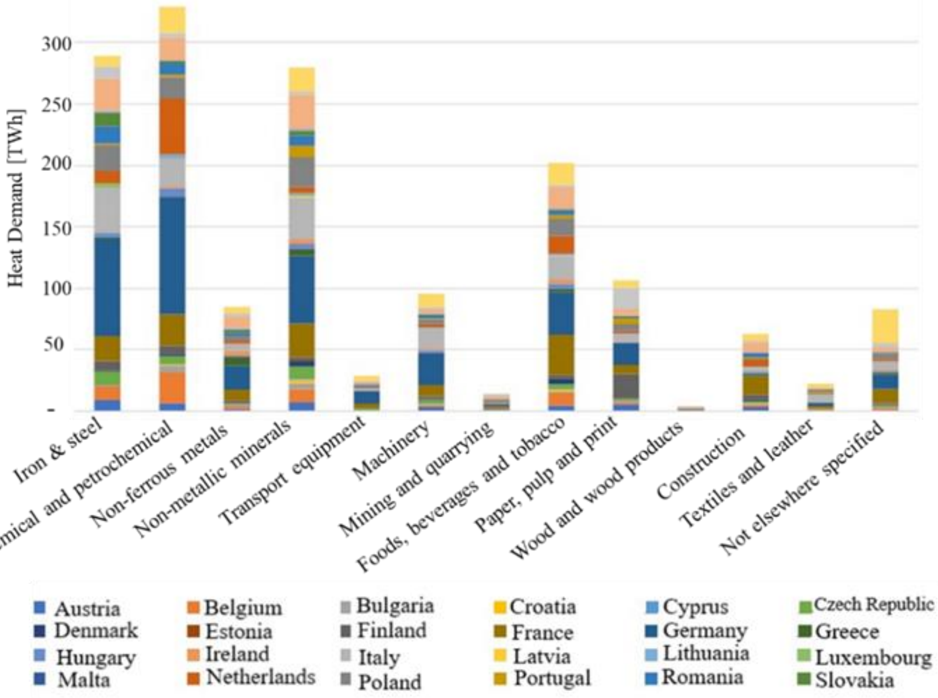

Figure 6. Breakdown of heat demand by industry in terawatt-hours (TWh) for the year 2015 [27].

The industrial sectors exhibiting the lowest heat demand were transport equipment (28.7 TWh), textiles and leather (22.2 TWh), mining and quarrying with a value of 13.9 TWh, and wood products with a value of 3.7 TWh as shown in Figure 6 [7,26]. Thus, the industries with the greatest heat demand were identified in Germany, France, Italy, Spain, and the United Kingdom. Within the EU28, the SPIRE industries exhibited the highest overall heat demand.

3.3. Heat Demand Based on the Temperature Range for Industrial Sectors in the EU28

Figure 7 illustrates the heat demand per temperature range of the primary industrial sectors in the EU for 2015. These data are derived from the EU heat demand for 2015, and information on the demand breakdown by temperature range as provided by IRENA [28] and Kosmadakis [29]. In the IRENA classification, heat demand is initially divided into three temperature ranges: (a) below 150 °C, (b) 150–400 °C, and (c) above 400 °C. For this purpose, data from Kosmadakis [29] were used for temperatures below 60 °C and between 60–150 °C. The analysis shows that iron and steel, non-ferrous metals as well as non-metallic minerals have a relatively modest value of heat demand representing only 8% within the 60–400 °C temperature range, as depicted in Figure 7. In contrast, the chemical and petrochemical industry has a significant heat demand of 48% in the same temperature range, while the food and tobacco industry exceeds 90%, as shown in Figure 7. The results demonstrate that in the 60–400 °C temperature range, the shares of heat demand for mining and quarrying, transport equipment, machinery, textiles and leather, and other process heat are 92%, 89%, 89%, 77%, and 77%, respectively. Approximately 27% of the heat demand of processes in European countries is reported to be within the temperature range between 100 °C and 200 °C [30]. However, most of the demand heat for process heating is for higher temperatures.

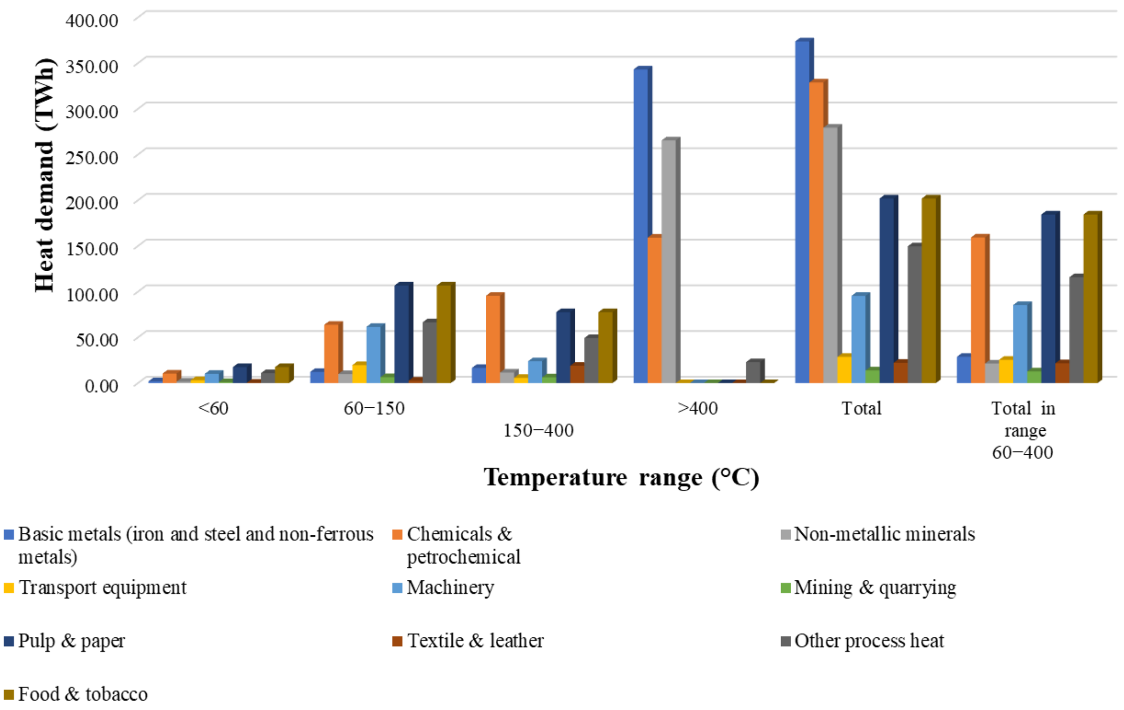

Figure 7. The heat demand categorized by temperature range for industrial sectors in EU28 [31].

3.4. Industrial Processes and Their Required Temperatures

Different industries and applications may require heat at different temperature levels to carry out their manufacturing or processing activities. Table 1 displays industrial processes requiring temperatures up to 250 °C that could potentially benefit from implementing the SUSHEAT system. These industries typically operate at temperatures below 250 °C, as indicated in Table 1 [27]. The food industry is commonly categorized as operating at low temperatures, for activities like separation and mixing, to as high as 250 °C for baking and frying [32]. Specifically, as shown in Table 1, in the canned food industry, the temperature requirements are typically within the range of 110 °C to 120 °C, primarily for sterilization processes [33]. In the dairy industry, the highest temperature required for drying milk powder is between 160 °C and 205 °C (see Table 1) [34]. In the water industry, the highest temperature required is in the range of 130–150 °C for wastewater evaporation [32]. The iron and steel manufacturing process consists of several stages, each with its temperature requirements. The temperature range for heating in this process is 180–220 °C, while the non-ferrous metal industry for drying processes requires temperatures of 60 °C to 200 °C (see Table 1) [31]. Nevertheless, by integrating heat pump systems with solar energy, it is possible to meet the significant heat demand required for different processes. This hybrid system can be used for various processes such as drying, washing, cooking, sterilizing, and pasteurizing [35–37].

Table 1. Potential industrial processes suitable for implementing the SUSHEAT System.

Industry	Processes	Required Temperature (°C)	References
Food and Beverages	Frying and baking	Up to 250	[32]
Canned food	Sterilization	110–120	[33]
Dairy	Drying	120–180	[34]
	Pasteurizing and Sterilization	60–145	[32,33]
Paper	Bleach	130–150	[33]

Table 1. *Cont.*

Industry	Processes	Required Temperature (°C)	References
Water	Evaporating of wastewater	130–150	[38]
Chemistry	Soaps	200–260	[38]
	Synthetic rubber	150–200	
	Process heat	120–180	[33]
Agricultural products	Drying	80–200	[33]
Textile	Degreasing	160–180	
	Drying	100–130	
Plastics	Drying	180–200	[33]
Wood products	Pulp preparation	120–170	[33]
Iron and steel	Heating	180–220	[31]
Non-ferrous metals	Drying	60–200	[38]

4. The Theoretical Potential (TP) of Implementing the SUSHEAT System across the EU28

In this section, the heat demand within the 150 °C to 250 °C temperature range was analyzed to assess the theoretical potential (TP) for implementing the SUSHEAT system in EU28 industries. The TP results for meeting heat demand are detailed in Table 2. These calculations were derived from the heat demand values shown in Figure 7, specifically for the temperature range of 150 °C to 250 °C. The theoretical potential relative to the total industrial heat demand was determined by dividing the heat demand of each industry by the total heat demand of 1600 TWh. The SUSHEAT system has a significant potential for application across all the industries listed in Table 2. As presented in Table 2, the total theoretical potential amounts to 134.92 TWh. The theoretical potential of the SUSHEAT system represents roughly 8.38% of the total industrial heat demand. According to the results obtained, the basic metals industry utilized 1.30% of its total heat demand for generating low and medium temperatures. Table 2 also highlights that the highest potential is found in the chemical industry (38.20 TWh), followed by the food and tobacco industry (31.04 TWh), pulp and paper (12.76 TWh), and machinery (9.56 TWh). The industry of chemicals and chemical products has a great heat demand (2.38%) and significant potential for incorporating the SUSHEAT system into different processes. The TP for the sector of transport equipment and textiles and leather industry is 2.28 TWh and 7.60 TWh, consisting of 1.68% and 5.63% of the total theoretical potential, respectively. These industrial sectors do not need heat at high temperatures above 400 °C, based on that reported in Figure 7. Anyway, the chemicals industry and food and beverages industries exhibited the greatest potential for using the SUSHEAT system, with a TP of 38.20 TWh and 31.04 TWh accounting for 28.31% and 23.00% of the total theoretical potential, respectively (Table 2). This sector does not need a high temperature of >400 °C. The paper and pulp industry has a theoretical potential of 12.76 TWh, representing 9.45% of the total TP outlined in Table 2. Other unspecified industrial sectors, including construction, wood and wood product manufacturing, and additional sectors outlined in the NACE Rev. 2 classification (Eurostat, 2023), have a TP of 19.72 TWh, which represents 14.61% of the total TP and 1.23% of total industrial heat demand.

Regardless of this, it is imperative to specify the heat consumption fulfilled by heat pumps and the proportion of the heat consumption by industry sectors. The conclusive step of this examination involves aligning the recoverable waste heat with the operation of industrial heat pumps to meet a portion of the heat demand.

Table 2. The theoretical potential of applying the SUSHEAT system in industrial sectors across the EU28.

Industrial Sectors	**Theoretical Potential [TWh]**	**Theoretical Potential over Total Industrial Heat Demand (%)**
Basic metals (iron and steel and non-ferrous metals)	6.64	0.41
Chemicals and chemical products	38.20	2.38
Non-metallic minerals	4.60	0.28
Transport equipment	2.28	0.14
Machinery	9.56	0.59
Mining & quarrying	2.52	0.15
Food & tobacco	31.04	1.94
Pulp & paper	12.76	0.79
Textile & leather	7.60	0.47
Other Process heat	19.72	1.23
Total	134.92	8.38

Figure 8 shows the overall heat consumption potential of heat pumps across all considered industries, highlighting the most favorable sectors. In addition, each bar in the temperature bands displays the percentage of heat consumption that can be addressed by the upgraded heat at the top of the bar. In the temperature range between 100 °C and 200 °C, industrial heat pumps exhibit the capability to cover a portion of favorable heat consumption across various sectors, excluding the industries of iron and steel, which lack any waste heat within this range and thus have zero potential. In sectors of non-ferrous metal, the potential of heat generation of heat pumps surpasses heat consumption by 11% (with 4.39 TWh/year of existing heat upgraded in comparison to 3.89 TWh/year of considered heat consumption). This allows for 100% coverage of heat consumption in the specified range of temperature (see Figure 8).

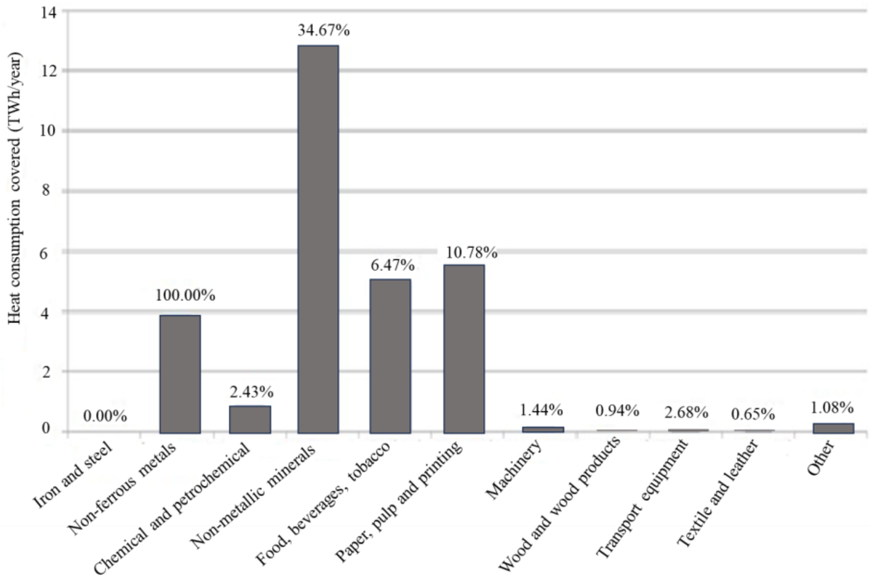

Figure 8. The heat consumption addressed by industrial heat pumps in the EU across all considered industrial sectors at 100–200 °C temperature range [29].

This proportion decreases to around 35% in the non-metallic minerals and drops to nearly 11% in paper industries (Figure 8). In the food sector, the proportion is roughly 6.5%, and in the chemical industries, it is even lower [29]. In industries with lower energy demand, the potential for sustainable solutions is notably limited, accounting for only

1–2% of heat consumption. Nevertheless, even within these sectors, viable sustainable approaches can be achieved, as seen in the textile industry.

5. Waste Heat in the Industries and Heat Pumps

5.1. Waste Heat per Industry in the EU28

A survey of energy consumption in the industries of the EU28 was conducted, and an initial evaluation of the potential for waste heat was made. The heat demand of processes and the potential for utilizing waste heat were calculated using a combination of industry-specific data, energy consumption profiles, and existing literature on industrial processes. A detailed analysis was conducted based on the energy requirements of each sector and the typical waste heat recovery potential associated with them. Table 3, based on information from reference [39], illustrates the shares of waste heat potential for individual industries. Table 3 indicates that the iron and steel sector accounts for the largest portion of waste heat with 11.40%, whereas the food and tobacco industry contributes 8.64% of the total waste heat. The distribution of energy consumption among 13 industrial sectors in 2016 was computed at 3217.85 TWh, with a predicted potential for waste heat with a value of 336.9 TWh [40].

Table 3. The percentage of waste heat potential per industry of the EU28 [39].

Type of Industry	Waste Heat Potential (%)
Iron and Steel	11.40
Chemical and Petrochemical	11.00
Non-ferrous metal industry	9.59
Non-metallic minerals	11.40
Food and Tobacco	8.64
Paper Pulp and Print	10.56
Wood and Wood Products	6.00
Textile and Leather	11.04
Other	10.38

5.2. Defining the Heat Demand of Processes and the Potential for Utilizing Waste Heat with Heat Pumps

Table 4 shows the calculated amounts of process and waste heat for the four industrial sectors within the temperature range of 15 °C to 200 °C (<200 °C) in the EU28. In addition, the amounts of processed and waste heat within the range of temperature below 150 °C are highlighted. The amount of waste heat is particularly noticeable in the refining sector, where the magnitude of waste heat significantly surpasses that of process heat. This characteristic is inherent to the sector, characterized by a significant demand for process heat at temperature values above 200 °C, which is subsequently removed from the given process at temperature values below 200 °C. Conversely, for other industries like paper and food, where almost all process heat is below 200 °C, the overall balance remains incomplete, resulting in a lack of comparability between process and waste heat values. The assessment of the processes identified a total of 1123 PJ/y of process heat and 1130 PJ/y of waste heat. The greatest amounts of process heat were also found in the paper and chemical sectors with 356 PJ/y and 355 PJ/y, respectively (see Table 4). The food sector and the refinery sector also showed significant amounts, although lower, with 193 PJ/y and 219 PJ/y, respectively. For waste heat, the refinery sector stood out with the highest calculated value of 465 PJ/y, followed by the chemical sector with 337 PJ/y, mainly due to the use of condensers in the processes of distillation. Significant sources of waste heat were found in the paper industry (231 PJ/y) and the food sector (97 PJ/y) [11] (see Table 4). In the current dataset, this issue is further compounded by analyzing process and waste heat within a specific temperature range, rather than considering heat across all temperature levels in the sector. This is particularly evident in the refinery sector, where waste heat significantly exceeds process heat. This is a characteristic of the sector, as it has high process heat demand at temperatures above 200 °C, but releases waste heat at temperatures below 200 °C. In contrast, sectors like paper and food, where nearly all process heat is below 200 °C, show an imbalance, making the process and waste heat values difficult to compare. The findings of this study suggest that the calculated heat pump market potential for the paper and chemical sectors is likely to reflect the actual potential. However, for the food sector, additional analysis is required to more accurately assess the heat pump market potential. Using high-temperature heat pump technology, the SUSHEAT project can convert a significant amount of excess waste heat into heat suitable for industrial operations, with an estimated yield of 47 TWh [30].

Table 4. An overview of the cumulative process and obtained waste heat (less than 150 °C and 200 °C (15 °C to 200 °C)) within the EU28 processes across the heat pump analysis [11].

	<150 °C		**15 °C to 200 °C (<200 °C)**	
Sector	**Process Heat (PJ/y)**	**Waste Heat (PJ/y)**	**Process Heat (PJ/y)**	**Waste Heat (PJ/y)**
Paper	228	231	356	231
Chemical	295	320	355	337
Food	130	96	193	97
Refinery	92	393	219	465
Total (Σ)	745	1039	1123	1130

To validate the effectiveness of the SUSHEAT concept, two main case studies were selected: the dairy industry Mandrekas, and the fish meal company Pelagia. The heat demand profiles for the two primary use cases, Mandrekas and Pelagia, detail the heating needs, design specifications, and operational constraints indicated in this work. Table 5 shows the specifications of the two case studies applied in this research work.

Table 5. The specification details of two case studies namely Mandrekas and Pelagia in this study.

	Company	
	Mandrekas	**Pelagia**
City/Country	Corinth/Greece	Bergen/Norway
Processes	Pasteurization (Milk/Yoghurt)	Drying (Fishmeal)
Heat Sources °C	Cooling of pasteurization products [(1) Milk and (2) Yoghurt]; liquid phase; 75–85 °C, temporal variability	(1) Dryer exhausts; humid air; approx. 60 °C; temporal variability. (2) Condensate streams; liquid water; 90 °C; temporal variability
Heat Delivered °C	Process steam; 8 bar; 175 °C	(1) Process steam; 8 bar; 175 °C (2) Hot air to dryers; 200–250 °C (3) Distillation re-boiler; 240 °C
Waste heat temperature	67–80 °C	70–98 °C
Total energy consumption (kWh)	LPG: 1,582,629	Thermal: 46,487,520 Electricity: 7,583,053

Case 1. Company Mandrekas: Mandrekas is a family-owned dairy company based in Corinth, Greece. This company produces a variety of yogurt, yogurt-based dressings, and also milk desserts such as rice pudding, chocolate and pudding cream. The plant uses 8 bar steam at 175 °C as its primary heating utility, generated by two LPG-powered boilers (see Table 5) one providing the base load (550 kW) and the other for peak load (350 kW). Table 5 shows that the production process in Mandrekas requires steam generation at 8 bar (175 °C) for milk pasteurization. Of the steam produced, 70%is used for pasteurization (operating at a pressure of 3 bar), 25% for yogurt ripening, and 5% for the sector of cleaning in place (CIP). The condensate is returned to the steam condensate tank as a saturated liquid at

1 bar and also at a temperature of 100 °C. Mandrekas calculated losses in steam generation and distribution to be 25%. However, there is potential for the use of the SUSHEAT concept in dairy processes to meet the heating requirements of the boiler (175 °C) as well as homogenization (67 °C), pressurization (80 °C), and mixing (28–30 °C). In addition, the developed HT-HP must drive a heat exchanger to produce 8 bar steam for seamless integration with the existing utility. While a comprehensive assessment of waste heat sources is being undertaken as part of this study, it is anticipated that waste heat from various pasteurization processes will be utilized. For example, pasteurized yogurt must be cooled from 85 °C to 45 °C, and pasteurized milk from 75 °C to 5 °C. The thermal energy storage system should therefore operate at around 65 °C. The nominal operating point of the heat pump involves a temperature rise from approximately 50 °C to 190 °C, allowing for reasonable pinch temperatures. This represents a significant technological innovation in heat pumps. The pilot-scale system being developed at SUSHEAT (200 kWth) is designed to replace approximately 57% of the peak-load boiler's capacity, or 22% of the overall boiler capacity.

The SUSHEAT system requires "on-demand" steam availability, necessitating high-capacity heat storage with rapid discharge capabilities. Given the required storage temperature of approximately 190 °C, the focus is on the use of salts. Innovation focuses on enhancing rapid discharge while addressing common design challenges such as corrosion and low thermal conductivity. The SUSHEAT system provides a storage capacity of 200 kWh (12.5% of daily heating demand) and could be capable of discharging at a rate of 200 kW. In any case, Mandrekas serves as a case study to validate the effectiveness of the SUSHEAT system, which includes integrating solar energy to raise the heat level to 190 °C. The data show a significant increase in energy consumption of Mandrekas over the last five years, from 752,019 kWh in 2015 to 1,582,629 kWh in 2019. Concerning waste heat in 2019, it is important to highlight that in Mandrekas, the waste streams from homogenization and pasteurization processes are at temperatures between 67 °C and 80 °C, respectively.

Case 2. Company Pelagia: Pelagia, based in Bergen, Norway, is a prominent producer of pelagic fish products for human consumption and a key supplier of vital ingredients for various fish and animal feeds, including protein concentrates, fish meal, and fish oil. The PEL's fish oil plant in Måløy, Norway, primarily relies on fuel oil for heating. Moreover, this plant consumes between 60–75 GWh annually to produce around 25,000 tonnes of fish meal and 8 tonnes of fish oil. In 2022, the Pelagia company recorded a total thermal energy consumption of 46,487,520 kWh and electricity consumption of 7,583,053 kWh as shown in Table 5. The fuel oil is utilized in three main areas: (1) in boilers to generate steam at 8 bar (175 °C) for heating cookers, dryers, and other process heating applications; (2) in the final drying stages to heat air to 200–250 °C; and (3) in distillation processes above 240 °C to remove polychlorinated biphenyls (PCBs) and heavy metals from omega-3 oil. The SUSHEAT system aims to provide heat across this entire temperature range, with the flexibility to adjust temperatures based on the plant's demand profile.

Table 5 demonstrates that waste heat in 2022 from the process in this plant comes from two main sources: (1) humid air streams from dryers at around 60 °C and (2) condensate streams at about 90 °C. At the Måløy plant, it is estimated to have 2 MW of waste heat at these temperatures, assuming minimal modifications to the process equipment in a heat pump retrofit scenario. Consequently, the SUSHEAT system must be able to capture waste heat within the 70–98 °C range and deliver it at temperatures between 150–250 °C. The benefits of a heat pump and thermal energy storage system effectively replacing the use of fossil fuel at Pelagia Måløy extend beyond just the test case and the fish oil/meal production sector. Both the waste heat sources and the heat consumers are crucial processes in the food processing industry and various other sectors. Meanwhile, in Pelagia, the temperature of the waste streams from the evaporation of dirty steam is between 95–98 °C, the dirty condensate is at 75 °C, and the humid air from the hot air dryer reaches 70 °C.

It is worth mentioning that the heat pump used in the SUSHEAT concept achieves a COP of 2.8 with a temperature ratio of 1.26, operating within a temperature range of

165 °C to 250 °C. Additionally, for temperatures ranging from 70 °C to 250 °C, the COP is measured at 1.9 with a ratio of 1.52 for the Mandrekas and Pelagia systems. In the case of the Mandrekas company, in a new configuration of the system, FLR collectors and ambient heat are utilized to supply heat for the high-temperature heat pump, whereas in the Pelagia company, only waste heat is recovered to heat the working fluid.

6. Environmental Advantages of Implementing the SUSHEAT System in the EU 28

Deploying the SUSHEAT system, which integrates solar energy systems with Stirling high-temperature heat pumps, in industries that need temperatures between 150–250 °C could significantly reduce GHG emissions. Combining high-temperature heat pumps, solar Fresnel collectors, thermal energy storage, and a CIT system improves the overall energy efficiency of the system. However, this also helps to optimize the use of renewable energy and reduce the need for backup fossil fuel-based energy sources. In addition, this system can provide substantial reductions in CO_2 emissions by using electricity (which can be generated from renewable sources) to produce heat instead of burning fossil fuels. The EU28's industrial sector emitted approximately 2.5 billion tonnes of CO_2-equivalent (CO_2e) in 2020 [41]. The transition from fossil-fuel-based systems to the SUSHEAT system offers a substantial opportunity for energy savings. The SUSHEAT project can potentially reduce GHG emissions by up to 145 g CO_2/kWh per year (excluding contributions from solar energy), based on the EU's 2020 emissions intensity and natural gas consumption levels. Considering the previously calculated theoretical heat demand potential of 134.92 TWh, the SUSHEAT system is expected to generate annual CO_2 emission savings of 19.4 million tonnes. It reduces greenhouse gas emissions, lowers energy consumption, minimizes air and water pollution, supports renewable energy targets, and promotes economic and environmental sustainability. Hence, by reducing greenhouse gas emissions and improving energy efficiency, this system plays a crucial role in mitigating climate change impacts, aligning with the EU's climate action goals. Overall, this research contributes to advancing knowledge in energy systems, providing a scalable model for decarbonizing industrial heat supply, and supporting sustainable practices across Europe.

7. Conclusions

The SUSHEAT system addresses the main technological challenges associated with developing key components for a new generation of greatly efficient industrial heat upgrade systems, utilizing renewable energy sources, waste heat recovery, and ambient heat. The SUSHEAT system includes an HTHP, a bio-inspired PCM TES system, and a CIT system. This study assesses the potential application of the SUSHEAT project concept to lower carbon emissions in the heat demand of the European industry. The classification of heat demand into temperature ranges as low, low-medium, medium, and high-temperature served as the basis for assessing the technical potential of HTHP systems to provide low-carbon heating for industrial processes. This study provides thermal demand profiles for two main use cases, namely Mandrekas and Pelagia industries, outlining their heating requirements, design specifications, and operating limits. The innovative SUSHEAT concept designs were introduced, providing adaptable solutions to address the heat requirements of the European industry. Potential industrial sectors for the use of the SUSHEAT system include food and beverages, plastics, desalination, textiles, ceramics, pulp and paper, wood products, canned food, agricultural products, mining, desalination, and chemistry sectors. The results depicted that the total heat demand for the EU28 amounted to 1600 TWh. In addition, the allocation of energy consumption across 13 industrial sectors in 2016 amounted to 3217.85 TWh, with an estimated value of potential for waste heat reaching 336.9 TWh. The results showed that the total theoretical potential is 134.92 TWh. Furthermore, the SUSHEAT concept of heat pump technology can transform a considerable portion of the surplus waste heat potential into heat for industrial processes, estimated at 47 TWh. For these specified industrial sectors, the industrial heat demand was quantified in the temperature range of 150 °C to 250 °C, which is achievable by the SUSHEAT system. The SUSHEAT system could reduce GHG emissions by up to 19.4 million tonnes per year (excluding solar energy contributions), using the EU's 2020 emissions intensity and natural gas benchmarks, significantly aiding the EU industry's 2050 net-zero GHG targets. However, combining different renewable energy sources with existing plant waste energy and incorporating a thermal storage energy system present a promising strategy for managing energy flows, enhancing available heat, and optimizing resource dispatchability. By analyzing the specific heat requirements of various European industries, the research identifies sectors that can benefit most from the SUSHEAT system. This targeted approach enables more effective implementation strategies tailored to industry needs. In addition, by aligning with European decarbonization targets, the study not only addresses immediate industrial heat requirements but also contributes to broader climate goals. This alignment enhances the relevance of the research in the context of global sustainability efforts. In other words, the comprehensive information presented here invites a thorough exploration of the potential of the SUSHEAT to contribute significantly to the decarbonization of heat demand in the European industrial landscape. The findings set a foundation for future research on similar technologies and their applications in other regions or sectors, promoting further exploration into efficient heat supply solutions that leverage renewable and waste energy sources.

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