

Electrifying European industrial heat: mapping of heat demand, technologies and applications

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ABSTRACT

Industry accounts for approximately 20% of total CO₂ emissions in the European Union, making it a key sector in the effort to achieve climate neutrality. However, its decarbonization remains particularly challenging due to a combination of technical, economic, and infrastructural constraints. The so-called "hard-to-abate" sectors, characterized by high-temperature heat requirements, and slow capital stock turnover, are often underrepresented or poorly characterized in energy system models. A critical barrier to their integration in long-term planning models is the lack of detailed, harmonized data on industrial heat demand across sectors, temperature levels, and geographical regions, as well as the underrepresentation of viable low-carbon technologies within these models. In this work, we address this gap by developing a comprehensive and consistent mapping of industrial heat demand across 12 industrial sub-sectors in 27 EU countries. The dataset distinguishes heat demand by temperature levels, low (<100°C), medium (100–400°C), high (400–1000°C), and very high (>1000°C), and identifies the corresponding potential for electrification via power-to-heat technologies. We complement this with a comprehensive review of current and emerging power-to-heat and storage technologies for industrial thermal processes. The key result of this study is a harmonized, open-access dataset of heat demand and adequate technologies, designed to support the improved representation of industrial heat demand and electrification pathways in energy system models. By refining both the spatial and sectoral resolution and the technological

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This document is the authors' preprint, prepared before peer review. The results reflect an earlier version of the IndustryHeat-EU database (v1.0.0). The peer-reviewed version of this work has been published as "Electrifying European industrial heat: mapping of heat demand, technologies and applications" in *Renewable and Sustainable Energy Reviews* (2026). The results in the published paper are based on IndustryHeat-EU (v1.2.0). The published version of record is available at <https://doi.org/10.1016/j.rser.2026.117541>. Please cite the published article.

detail, our work enables more accurate modelling of decarbonization pathways for hard-to-abate sectors through direct electrification.

KEYWORDS

decarbonization, energy modelling, industrial process heat, sector coupling.

Word count: 9774

1. INTRODUCTION

Everything we wear, eat, and use is produced in industrial facilities largely built around fossil fuels [1]. These systems are slow to change, capital-intensive, tightly regulated, and shaped by decades of fossil-dependent design. Many industrial processes do not simply consume fossil fuels – they are structured around them, with implications for product standards, performance, and process engineering [2]. Decarbonizing these sectors means replacing mature, fossil-based technologies for high-temperature process heat with clean alternatives, without compromising reliability or cost. But innovation in these hard-to-abate industries, such as cement and steel, entails high technical and economic risks [3]. Industrial process heat remains one of the most carbon-intensive segments of the energy system, and due to its critical role in manufacturing, it should be a key focus of decarbonization efforts.

Multiple decarbonization pathways have emerged, such as biomass combustion [4], waste heat recovery [5], hydrogen-based fuels [6], and carbon capture [7], each facing its own challenges. In parallel, declining costs of renewable energy sources and progress in power-to-heat technologies have revived interest in direct electrification [8]. Despite this momentum, the academic literature exhibits two persistent inconsistencies – one related to national heat demand mapping across consistent temperature bands and another one related to the lack of techno-economic data, impeding rigorous cross-sectoral analysis.

1.1. Literature review

Quantifying industrial process heat typically involves categorizing it into low-, medium-, and high-temperature bands. At the EU level, no comprehensive dataset currently exists that disaggregates *useful* energy demand for industrial heat by country, sector, and detailed temperature bands. Most available studies are limited either in scope, in resolution or deal with final energy demand.

Zazzera et al. [9] attempt to overcome some of these limitations with a top-down approach that disaggregates national statistics into a site-level database for Italy, including four process heat temperature categories. While the methodology is general, the analysis and data are country-specific and tied to Italy. Rehfeldt et al. [10] present a bottom-up inventory of final energy demand for process heat across EU28+3 countries and three temperature ranges: $<100\text{ }^{\circ}\text{C}$ (228 TWh), $100\text{--}500\text{ }^{\circ}\text{C}$ (706 TWh), and $>500\text{ }^{\circ}\text{C}$ (1,035 TWh) for the year 2015. Such final energy metrics are influenced by conversion efficiencies and are therefore less suitable for modelling purposes than useful energy estimates [11].

Similarly, Naegler et al. [12] estimate industrial heat demand by industry branch and temperature classes for EU27, while Kosmadakis [13] and Marina et al. [14] provide refined estimates for specific temperature intervals and heat pump market potential, respectively. Madeddu et al. [15] provide one of the most comprehensive assessments by evaluating both final and useful energy demand across 11 industrial branches, distinguishing between electrified and non-electrified heat with $100\text{ }^{\circ}\text{C}$, $400\text{ }^{\circ}\text{C}$ and $1000\text{ }^{\circ}\text{C}$ as temperature thresholds. However, their results are aggregated at the EU27+UK level and do not support country-level

resolution. All these studies typically lack simultaneous disaggregation by country, sector, and temperature band.

As a result, the representation of industrial heat in energy planning studies is highly inconsistent and case-specific, complicating cross-comparisons [8]. In the energy modelling literature, some authors define high-temperature processes as those exceeding 100 °C [16] [17], while others set thresholds at 400 °C [18], 800 °C [19], or even 1000 °C [20]. Pastore et al. [21] propose a more granular distinction (<80 °C, 80–150 °C, and >150 °C), whereas the LUT model applies low (up to ~100 °C), medium (150–1000 °C), and high (>1000 °C) bands [20,22,23]. The lack of a standardized framework highlights the need for better harmonization in energy modelling to ensure technology-agnostic policy support [8].

Several recent studies focus on the promising potential of electrification. Madeddu et al. [15] estimate that near-complete electrification of industry could lead to a 78% reduction in CO₂ emissions. Fleiter et al. [24] and the Fraunhofer Agora study [25] further report that process heat accounts for approximately 75% of industrial CO₂ emissions and that electric technologies available by 2035 could meet up to 90% of today's heat demand. Despite these findings, process heat electrification remains *underrepresented* in mainstream energy system models.

Knorr et al. [8] systematically review how industrial heat is treated in models and identify two major limitations: most analyses concentrate on low-temperature applications and neglect flexibility and high-temperature options. As a result, emerging technologies, such as high-temperature thermal storage, electric calciners or plasma torches are not always considered in models, which skews results in favour of indirect electrification and molecule-based mixes [26]. They recommend improvements in three areas: (1) harmonized temperature classifications, (2) comprehensive datasets of process heat demand and technologies, and (3) better integration of electrification options into modelling frameworks.

1.2. Contribution

This study aims to address the identified data and modeling gaps, by answering two central research questions:

- What is the industrial useful heat demand by sector, temperature level, and country across the EU?
- What are the values of techno-economic parameters of candidate direct electrification technologies for the specified temperature bands?

By answering these questions, we develop a harmonized, open-access dataset of industrial process heat demand for 12 key sub-sectors across all 27 EU countries. Heat demand is disaggregated into four temperature classes (low: <100 °C; medium: 100–400 °C; high: 400–1000 °C; very high: >1000 °C), addressing the lack of consistency noted in the literature and aligning the results with the temperature classification of EU's Innovation Fund's pilot heat auction (IF25) [27]. The dataset quantifies useful energy demand by country, sector, and temperature band, enabling fine-grained spatial and sectoral analysis. In parallel, we provide a comprehensive review of current and emerging power-to-heat and storage technologies applicable to each temperature range. For each class, we identify suitable applications—including heat pumps, electric boilers, and electric arc furnaces—and compile their key technical and economic parameters. This creates a direct linkage between sectoral heat demand and viable decarbonization technologies, supporting energy system modellers. Finally, we respond explicitly to the modelling challenges outlined by Knorr et al. [8], offering temperature classifications aligned with associated technologies and contributing to a "validated database

for scalable energy systems" and the "determination of reasonable temperature levels... with associated technology options."

2. METHODS AND MATERIALS

The heat demand mapping of the industrial sector is based on the 2021 Joint Research Centre's Integrated Database of the European Energy System (JRC-IDEES) [28]. The dataset comprises energy system data for the European Union, covering the residential, tertiary, transport, and industry sectors, among others. It ensures compliance with Eurostat and offers improved accuracy compared to the JRC-IDEES-2015 dataset. The JRC-IDEES-2021 dataset provides information on final energy consumption, useful energy demand, and CO₂ emissions for the industry sector in EU27 countries. Our focus is on the useful energy demand in iron and steel, non-ferrous metals, chemicals, non-metallic minerals, pulp and paper, food, beverages and tobacco, transport equipment, machinery equipment, textiles, and wood products. Within the non-metallic minerals sector, cement is analyzed separately from ceramics, glass, and other non-ferrous metals. Pharmaceutical products were not considered within the chemicals industry due to their small contribution to the sector's CO₂ emissions. Similarly, printing and media reproduction are omitted from the pulp and paper sector.

The energy demand in each sector is disaggregated by industrial process (e.g. general machinery, steam processing, furnaces, calcination, smelting, product finishing). As processes vary across sectors, a common categorization is required to enable consistent analysis of energy demand. To this end, the energy use of each process is mapped into seven standardized categories of industrial energy use, following the methodology of Madeddu et al. [15].

The analysis distinguishes between electrified and non-electrified energy demand. The electrified energy demand includes 1) energy for thermal processes, such as low-enthalpy heat, and 2) electricity for other applications, such as lighting, compressors, motors, pumps etc. Non-electrified process heat derived from fuel combustion is differentiated by its temperature level: low (<100°C), medium (100–400°C), high (400–1000°C), and very high (>1000°C). The analysis is conducted individually for each EU27 country, addressing methodological limitation of previous studies related to spatial resolution [9,15], and the inclusion of both electrified and non-electrified process heat sources [10,29]. This approach allows for a more realistic assessment of suitable decarbonization technologies. A detailed overview of the mapping is given in Table A.1. The complete dataset, title IndustryHeat-EU, is made available on Zenodo [30].

Finally, a comprehensive review of technologies and application for direct electric heating is conducted. A synthesis of key parameters, such as temperature range, capital and operational costs, efficiency, typical capacities and estimated technological lifetimes, and contextualize them through real-world case studies in sectors different sectors. The goal is to provide empirical grounding for representing industrial power-to-heat technologies for future techno-economic analysis and energy system modelling. These parameters and applications serve as the bridge between technical feasibility and model-based policy design for industrial decarbonization.

3. EUROPE'S INDUSTRIAL HEAT DEMAND

Decarbonization of high-temperature industrial process heat is widely considered one of the greatest challenges in climate change mitigation. Process-specific requirements, limited technological maturity, high investor risk aversion, long capital stock turnover, and the prevailing assumption that process heat inherently requires high temperatures are among the key reasons. While the EU27 industry indeed exhibits significant energy demand for heat above

1000 °C, a closer examination of the distribution of industrial heat demand raises important questions about this conventional framing. This section presents a detailed analysis aimed at reassessing the temperature profile of industrial heat demand across the EU27. The analysis proceeds in two parts: first, a revision and expansion of the EU-wide assessment by Madeddu et al. [15], and second, a country-level disaggregation that provides more granular insights. The results have important implications for energy modellers seeking to improve spatial resolution and for policymakers aiming to align industrial decarbonization efforts with national circumstances.

3.1. Mapping industrial heat demand by end use

The total useful energy demand in the EU27 industry sector was 1311 TWh in 2021, of which 1040 TWh is attributed to process heat. Approximately 42% of this process heat is required at temperatures below 400 °C, primarily for applications such as steam generation, space heating, process cooling, drying, and thermal treatment (Figure 1). When electricity is excluded, this low- and medium-temperature heat accounts for 53% of all heat derived from fossil fuel combustion, which is a major source of CO₂ emissions (Table 1).

Among end-uses, steam processes constitute the largest share at 408 TWh, followed by electricity for general purposes (271 TWh), and non-electric high-temperature heat (>1000 °C), which amounts to 251 TWh and is predominantly consumed in primary steel production, cement, and non-metallic minerals. An overview of the total useful energy demand across the EU27 is provided in Table 2.

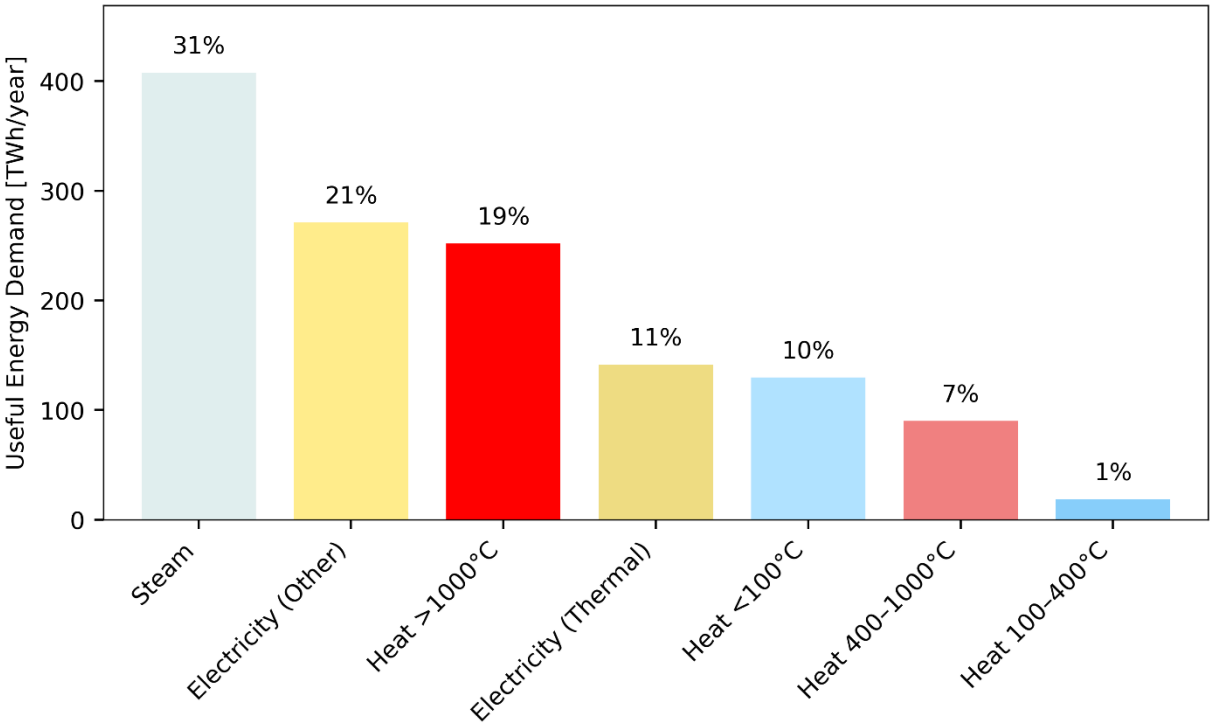


Figure 1.Total useful energy demand by industrial energy use in EU27 (TWh/year).

Table 1. Distribution of industrial heat demand in the EU, by temperature level in 2021, expressed as a percentage (%) of total useful heat demand (excluding electricity use for general machinery and appliances).

Electricity (Thermal)	Steam	Heat (<100°C)	Heat (100-400°C)	Heat (400- 1000°C)	Heat (>1000°C)
14	39	12	2	9	24

About half of the total industry demand is associated with only three industries - the pulp and paper, chemicals and food industries. Together, they account for 646 TWh, or 49% of the total useful energy demand of 1310 TWh. Around 68% of their demand requires temperatures below 400°C. As shown in Figure 2, we observe that primary steel production is not the largest consumer of energy – a result that counters a viewpoint previously held by multiple authors [15],[10,12]. This correction does not come from the methodology for mapping industrial energy use across end uses, but from the methodological differences applied by JRC in compiling the 2021 dataset compared to 2015 and the fact that these results refer to useful energy. For example, according to JRC-IDEES-2021, the useful energy of primary iron in 2015 is 168 TWh, while according to JRC-IDEES-2015 it is equal to 293 TWh. Another difference relates to how space heating is treated and disaggregated in 2021 compared to the 2015 dataset, highlighting the value of continuous data quality control for informed decision making.

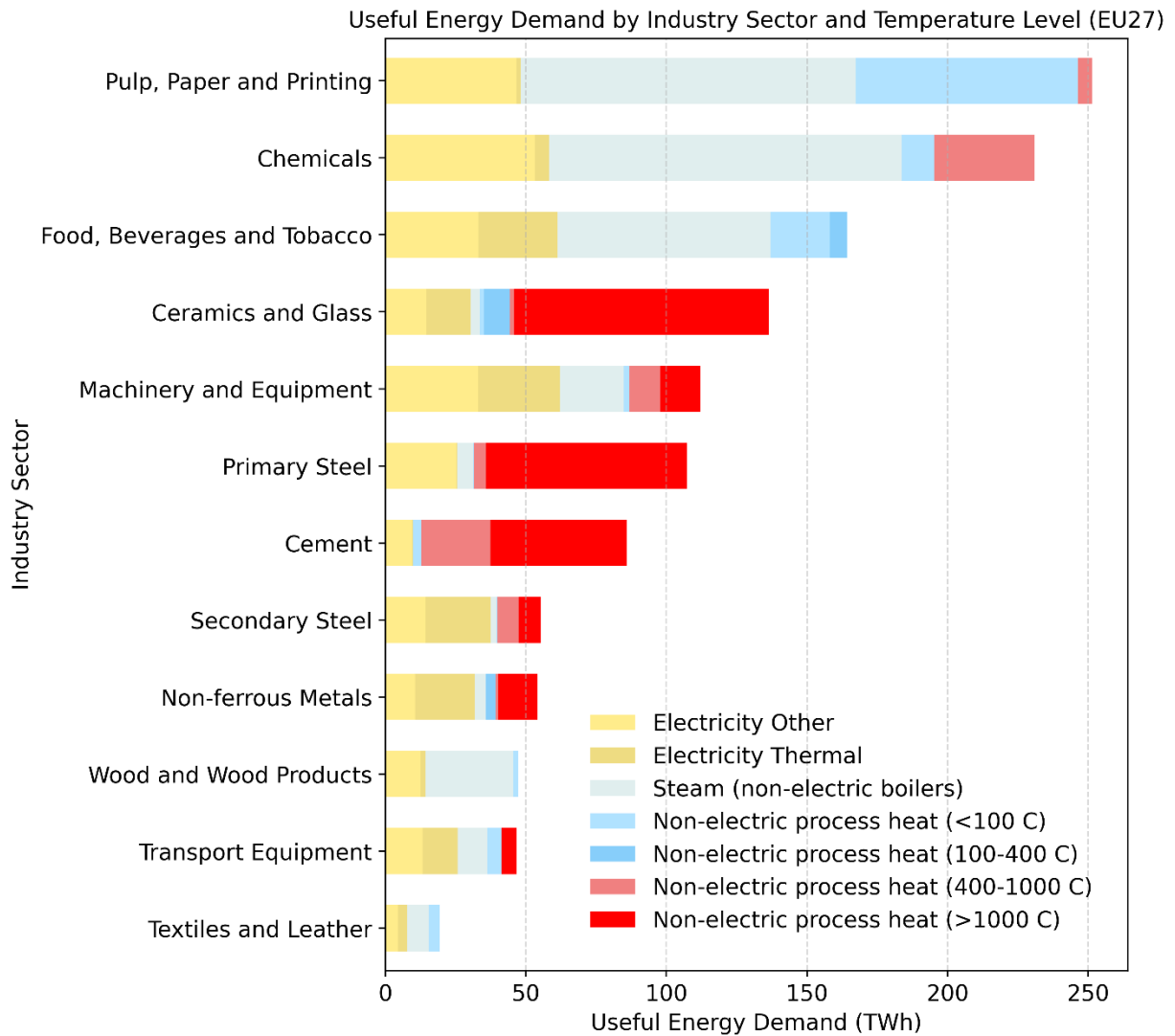


Figure 2. Useful energy demand by industrial sector in EU27 for 2021 (TWh/year).

3.2. Country-level assessment of industrial heat demand

A spatially resolved analysis is essential to better understand the distribution and implications of industrial energy demand across Europe. Industrial facilities are often closely integrated with local communities, influencing not only regional CO₂ emissions and economic development but also local identity. Figure 3 shows how individual industrial plants are distributed across Europe, based on location-specific data from [31].

The five largest energy consumers – Germany, Italy, France, Spain and Poland – collectively account for 60% of the EU27's total useful industrial energy demand (Figure 4). Expanding the scope to the top ten consuming countries raises this share to 84%. The top five countries have significant potential for short-term decarbonization of industrial process heat, as their heat demand below 400 °C accounts for 23% of all EU useful energy in industry.

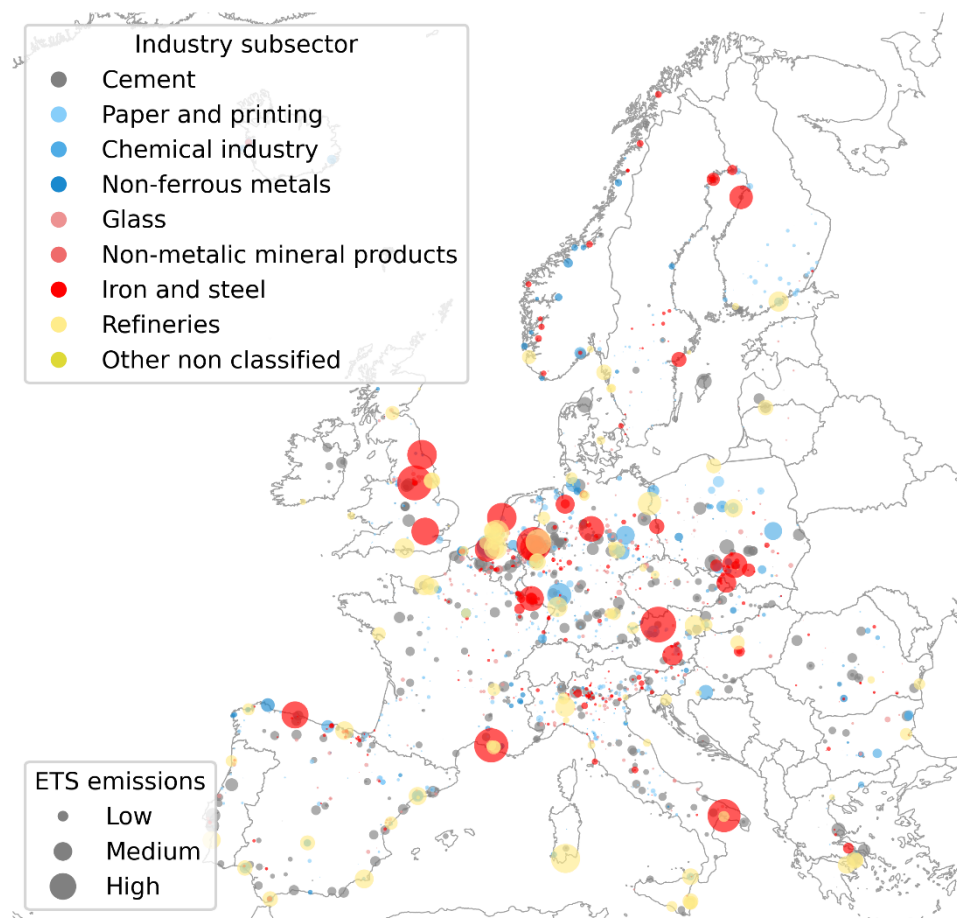


Figure 3. Illustration of spatial distribution of different industrial facilities across Europe, based on Hotmaps database.

Table 2. Useful energy consumption (TWh/year) in industry in EU27, per category, temperature range and country

	Elec. (other)	Elec. (therm.)	Steam	<100 C	100-400 C	400-1000 C	>1000 C	Total
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DE	68.22	31.42	96.97	18.14	3.72	22.37	66.21	307.04
IT	30.52	23.99	43.59	8.24	2.34	11.66	32.86	153.20
FR	30.57	18.74	40.26	10.43	2.54	7.84	25.87	136.25
ES	20.98	13.01	27.54	9.18	2.20	8.05	24.57	105.54
PL	15.50	7.83	25.56	6.05	1.11	5.99	18.86	80.90
NL	12.63	3.81	41.55	4.88	0.67	7.94	6.71	78.19
SE	17.13	5.34	19.84	21.88	0.07	1.70	4.44	70.40
FI	15.00	3.45	21.47	22.75	0.09	1.26	3.51	67.54
BE	12.61	4.56	21.49	4.28	0.80	5.27	10.12	59.14
AT	8.98	3.24	15.47	5.44	0.50	2.27	9.09	44.98
CZ	7.16	3.43	9.93	3.40	0.45	2.45	9.40	36.22
RO	4.96	4.33	7.34	1.42	0.80	3.42	8.25	30.52
PT	5.34	2.56	6.49	5.89	0.32	1.52	4.16	26.28
HU	4.95	2.70	7.21	1.29	0.39	1.45	3.43	21.42
SK	3.29	2.26	3.91	1.99	0.21	1.29	6.02	18.97
EL	2.51	2.89	2.10	0.43	0.46	1.44	3.35	13.18
BG	1.93	1.46	3.14	0.83	0.21	0.76	2.95	11.28
DK	1.81	1.50	2.63	1.07	0.34	0.40	2.94	10.68
IE	1.65	0.93	2.41	0.57	0.96	0.82	3.29	10.64
SI	1.20	1.36	1.55	0.29	0.18	0.62	1.04	6.23
HR	1.05	0.58	1.53	0.30	0.13	0.32	1.71	5.62
LT	1.03	0.42	2.44	0.36	0.04	0.39	0.70	5.38
LV	0.67	0.24	2.42	0.16	0.05	0.07	0.84	4.45
LU	0.43	1.01	0.24	0.04	0.00	0.73	0.76	3.21
EE	0.72	0.27	0.53	0.29	0.01	0.03	0.09	1.94
CY	0.14	0.09	0.10	0.03	0.03	0.11	0.72	1.21
MT	0.06	0.07	0.02	0.00	0.00	0.00	0.00	0.16
EU27	271.02	141.50	407.75	129.62	18.62	90.17	251.89	1310.57

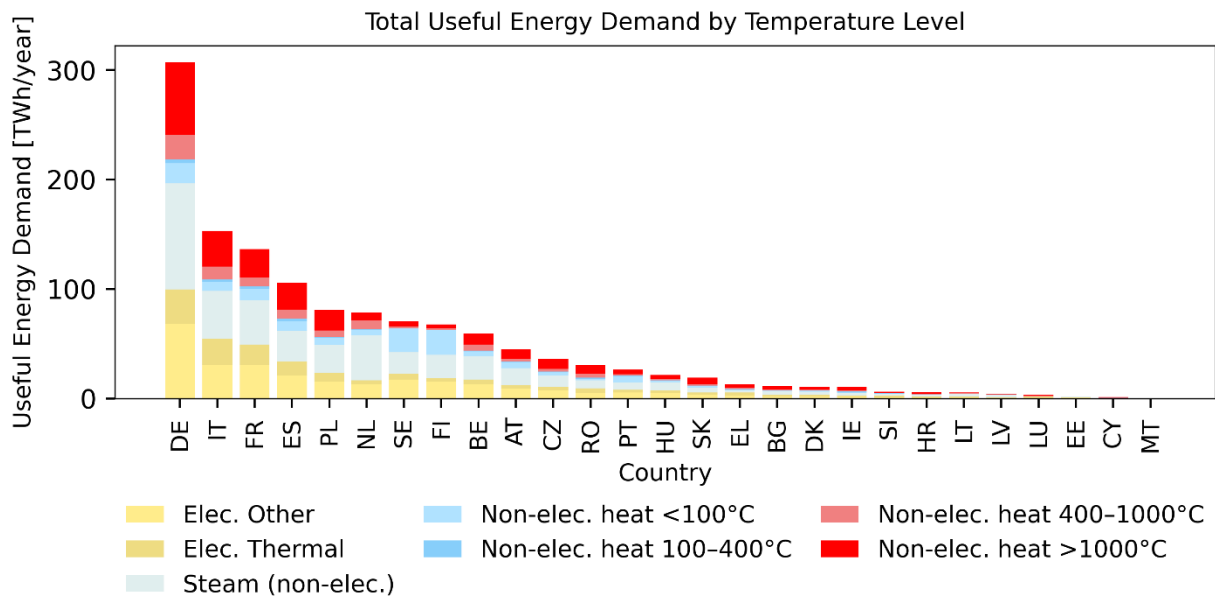


Figure 4. Useful energy demand by temperature level in different EU27 countries (TWh/year)

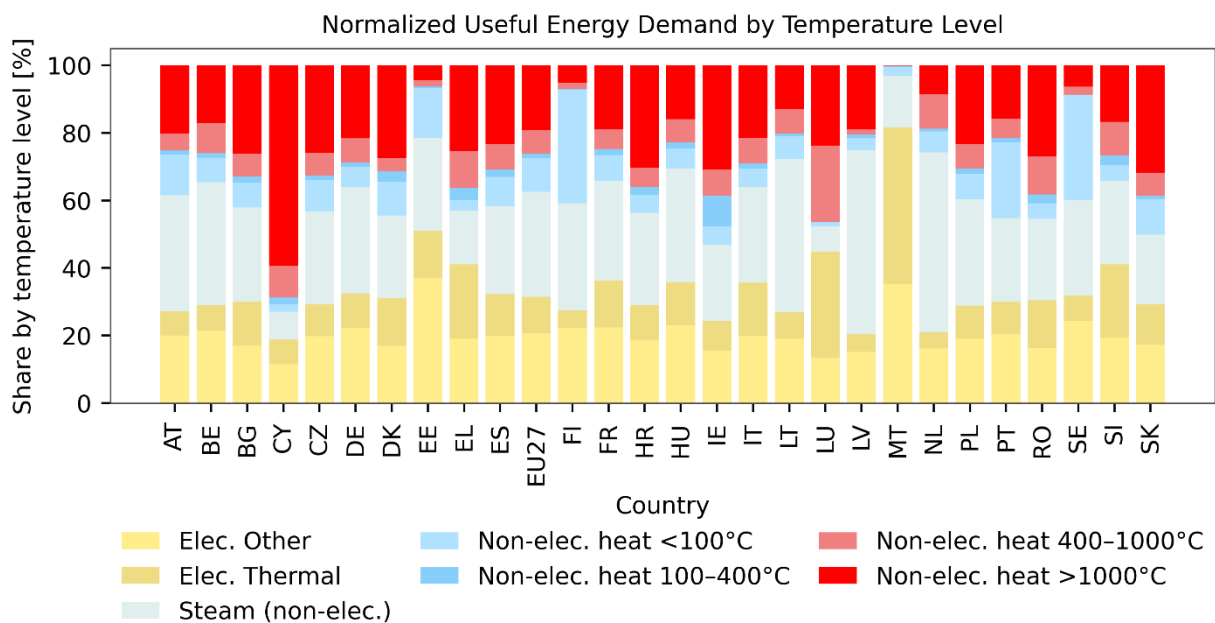


Figure 5. Distribution of industrial useful energy demand across different energy uses in EU27 countries (TWh/year).

However, industrial heat demand profiles differ substantially across countries, reflecting variations in their industrial sectors and process requirements. This diversity complicates decarbonization, as tailored solutions must align with specific local industrial characteristics rather than relying on direct knowledge transfer from neighboring countries.

For example, Germany's industrial sector has a pronounced demand for very high-temperature heat ($>1000^{\circ}\text{C}$), totaling 66.21 TWh, alongside a large steam demand of 96.97 TWh. Spain's industrial heat demand includes significant contributions from the glass and ceramics sectors, which consume approximately 13 TWh (12.4% of Spain's total industrial heat demand of 105.5

TWh). This indicates a dominant role of medium- to high-temperature processes in Spain's industry. Similarly, smaller economies like Cyprus demonstrate low overall demand (1.21 TWh) but with a disproportionately large share (around 59%) at temperatures above 1000 °C, largely due to cement, ceramics, and glass production.

In Northern Europe, countries such as Finland and Sweden exhibit industrial demand profiles dominated by lower temperature heat and steam, especially in pulp and paper industries. In Finland, these processes represent over half of the total industrial heat demand (36.2 TWh out of 67.5 TWh). Similarly, in Sweden, steam demand in pulp and paper accounts for nearly 50% of national industrial heat consumption. All values reflect useful energy demand. Both countries utilize biomass extensively for steam generation through cogeneration and biomass boilers. While the specific incentives to switch fuels are not yet fully established, there is economic rationale for transitioning toward electrification technologies given the favourable electricity-to-gas price ratio in these countries. Switching to direct electric heating could also release biomass resources for alternative uses. These contrasting temperature profiles and sectoral emphases across Europe highlight the need for a nuanced understanding of industrial heat requirements.

4. INDUSTRIAL POWER-TO-HEAT TECHNOLOGIES AND APPLICATIONS

Electrifying industrial heat is essential for making industry more sustainable and cost competitive. As fossil-based heating makes up a large share of industrial CO₂ emissions, shifting to power-to-heat solutions offers one of the most direct and scalable decarbonization levers. Core power-to-heat technologies convert electricity into heat through physical principles such as resistive (Joule) heating, induction heating, dielectric heating, infrared radiation, electric arc heating, plasma heating, and ambient heat transfer in heat pumps. Equipment like electric boilers, resistance furnaces, electric kilns, electric arc furnaces, and plasma torches are applications that implement these technologies to deliver heat for specific industrial processes.

In the text, technologies and their associated applications are frequently presented together to illustrate the link between the underlying physical mechanisms of heat generation and their practical implementation in industrial systems.

This section reviews the techno-economic characteristics of these technologies, spanning across a wide application and temperature spectrum. It also reviews the standard and emerging applications of each conversion method. The techno-economic parameters of the technologies evaluated in this paper are given in Table 3.

Table 3. Techno-economic parameters for industrial power-to-heat technologies

Technology	Temp. Range (°C)	CAPEX (€·kW ⁻¹)	Fixed O&M (€·MW ⁻¹ ·year ⁻¹)	Efficiency (η / COP)	Capacity range (MW(h))	Lifetime (years)	Ref.
Heat Pump	<60	700-880	2000	5.28-5.61	0.50-5.00	20	[32]
	<70	700-880	2000	4.42-4.69	0.50-5.00	20	[32]

	<70	700-880	2000	3.83-4.03	0.50-5.00	20	[32]
	<80	700-880	2000	3.28-3.48	0.50-5.00	20	[32]
	90-160	250-850	-	2.40-5.60	0.02-20	-	[32–35]
	<125	840-1050	720-970	2.55-2.85	0.50-5.00	20	[32]
	<150	1010-1250	720-970	3.00-3.25	0.50-5.00	20	[32]
	<150	1120-1960	2000	1.98-2.10	1.00-15.00	20	[32]
	<200			1.50-6.00	0.66-20.00	-	[25]
Electric boiler (direct and indirect resistance heating)	<150 ¹	240-280	920-1070	0.99	0.06-5.00	25	[32]
	<150 ²	110-130	828-963	0.99	0.06-5.00	25	[32]
	<200 ³	190-210	1058-1230	0.99	0.06-5.00	25	[32]
	<200 ⁴	80-100	952-1107	0.99	0.06-5.00	25	[32]
	200-400	238	4750	0.99	5-50	20	[19]
	<500	-	-	0.99	0.001-75		[25]
Indirect resistance heating (furnace, calciner, kiln)	600-1300 ⁵	-	-	0.50-0.90	0.01-0.30	-	[15]
	<1250 ⁶	-	-	0.75-0.97	-	-	[36,37]
	<1700	252€/t; 157 €/t ⁷	-	-	-	15	[38]
Dielectric heating	-	2430-2700	-	0.85-0.99	0.001-1.00	30	[32]
	<400	-	-	0.50-0.60	0.006-0.30	-	[36]
	<2200	-	-	0.70	-	-	[25]
Infrared heating	400-600	320-350	-	0.50-0.60	0.01-0.20	30	[32]
	800-1800	320-350	-	0.80-0.85	0.01-0.20	30	[32]
	1800-2500	320-350	-	0.85-0.90	0.01-0.20	30	[32]

	<1370	-	-	0.70-0.96 ⁸	-	-	[25]
Induction heating	<1600	-	-	0.40-0.90	0.10-21	-	[36,37]
	<3000	-	-	0.90	<42	-	[25]
Electric arc heating	<1750	-	-	0.65-0.90	10-150	-	[36,37]
	<1800	-	-	0.90-0.95	<200	-	[25]
Plasma heating	<5000	-	-	0.50-0.90	0.005-8.00	0.23	[15,25,37]
Thermal storage	1000-1700	36 / 54 ⁹	-	<0.03/day ¹⁰	100-1000	-	[39]
	<1100	- ¹¹	-	0.98	300	40	[40]
	<250	13 ¹²	-	0.95 ¹³	100-500	25	[41]
	<300	92 ¹⁴	0.46-2.76 ¹⁵	0.92 ¹⁶	100-1000	25	[41]

¹(0.4-0.69 kV, hot water, 1-12 bar); ²(10 kW, hot water, 1-12 bar); ³(0.4-0.69 kV, steam, 1-12 bar); ⁴(10 kW, steam, 1-12 bar); ⁵(resistance furnace); ⁶(direct resistive heating); ⁷(new plant and refurbished plant); ⁸(0.85-0.96 for plastics; 0.70-0.90 for wood); ⁹(charge: 32 €·kW⁻¹, discharge: 48 €·kW⁻¹, capacity: 10 €·kWh⁻¹); ¹⁰(standby losses); ¹¹(present value of 2020-2050 lifecycle costs estimated between 2.7-8.1 €·kWh; <1%/day standby losses, modelled after Rondo RHB300 model); ¹²(charge: 120.4 €·kW⁻¹ (40.3-167.0 €·kW⁻¹), discharge: 30.1 €·kW⁻¹ (10.1-41.8 €·kW⁻¹), capacity: 13 €·kWh⁻¹ (4.4-18.1 €·kWh⁻¹)); ¹³(charge: 0.99, discharge: 0.96); ¹⁴(capacity: 31-109 €·kWh⁻¹); ¹⁵(0.5-3% of CAPEX (€·MWh⁻¹)); ¹⁶(charge: 0.98, discharge: 0.95);

4.1. Heat pumps

Heat pumps combine moderate capital expenditures with high operational efficiency to unlock decarbonization of low to medium temperature process heat. Leveraging existing waste-heat streams, often at 30–80 °C, heat pumps lift temperature to useful level with minimal additional energy input. By replacing or augmenting gas-fired boilers, industrial heat pumps cut CO₂ emissions and utilize renewable electricity [15]. In the European Union, the potential market for high-temperature heat pumps is estimated between 28-178 TWh/year, as shown in Table 4.

Table 4. Potential heat demand that can be supplied by industrial heat pumps

Region	Temp range (°C)	Heat (TWh/year)	Ref.
EU	≤ 150	15-51	[13]
EU	≤ 200	178	[14]
EU	≤ 150	174	[35][42]
Switzerland	-	24	[35]

Germany	≤ 140	170	[35]
France	≤ 140	33	[35]

4.1.1. Techno-economic parameters

Heat pumps are well established for low to medium temperatures (TRL9) with many commercial solutions readily available. Arpagaus et al. [35] give an overview of more than 26 heat pumps from 13 manufacturers with temperatures up to 165°C. Typical investment costs for industrial-scale units lie in the range of €700–850 €·kW⁻¹, depending on temperature level, refrigerant choice, and system complexity [32–35]. Despite these upfront costs, heat pumps deliver coefficients of performance (COP) between 3.0 and 6.0, which translates to three- to six-fold reductions in equivalent primary energy demand relative to direct electric heating and even more compared to natural gas boilers, especially for low to medium temperature applications (<120°C) [35,43]. Higher temperature heat pumps have higher installation costs of about 800-2000 €·kW⁻¹ and COPs in the 2-3 range.

4.1.2. Potential applications

The potential applications include food processing (starch and dryer systems) [44], textiles and pulp & paper (wash-water and drying loops) [45], chemicals and pharmaceuticals (steam generation for sterilization). High-temperature heat pumps can also produce steam for industrial processes. They are still at a prototype demonstration (TRL7-8) or even at lab validation (TRL4-5) for temperatures above 200°C. [46].

4.2. Dielectric heating

Dielectric heating refers to microwave (MW) and radiofrequency (RF) heating, both relying on dielectric loss in insulating or semi-insulating media. Thermal energy is generated when a dielectric material is exposed to an alternating electric field (10–30,000 MHz). RF heating typically uses 10–300 MHz, while MW heating operates at 300 MHz–30 GHz [36]. Heating arises from polarization effects: displacement of bound charges and limited conduction of free carriers. Since dielectric materials exhibit low electrical and thermal conductivity, conventional conduction and surface heating methods are ineffective, leading to slow heat penetration.

4.2.1. Techno-economic parameters

Dielectric heating enables volumetric, rapid, and uniform heating, reaching up to 2200 °C [25]. It is a non-contact process, offers precise thermal control, and is suited to materials such as plastics, ceramics, textiles, and food. Key advantages include selective heating based on dielectric properties, environmental friendliness due to lack of combustion gases, and adaptability across various sectors. However, high capital costs—ranging from €2430 to €2700 per kW—and limited capacity scale (0.001–1 MW) constrain its economic competitiveness compared to resistance or infrared heating [32]. Efficiency ranges from 0.85 to 0.99, with system lifetimes up to 30 years [25].

4.2.2. Potential applications

Common industrial uses include drying (textiles, paper, food), sterilization (medical and food), cement [47], sintering (ceramics) [48], plastic welding, and thermal processing in chemical industries [25]. MW heating dominates food applications (e.g., cooking, defrosting), while RF heating is suited for rubber vulcanization and wood drying. Microwave sintering has recently

gained attention for its energy efficiency and improved material properties over conventional sintering [49]. Despite its technical merits, dielectric heating remains niche due to high CAPEX and limited scalability, making it most suitable where precise, uniform, and contact-free heating is required within specific industrial contexts.

4.3. Infrared heating

Infrared heating utilizes electromagnetic radiation in the 0.78–1000 μm range to deliver thermal energy directly to object surfaces, bypassing convective or conductive intermediaries [32]. Governed by the Stefan–Boltzmann law, where radiative flux scales with the fourth power of absolute temperature, infrared systems can achieve processing temperatures between 400 °C and 1400 °C simply by raising emitter temperature. This direct delivery yields thermal efficiencies often exceeding 50–90 % at power density between 10–300 kW/m^2 , both improving for lower wavelengths [32]. Moreover, infrared units boast near-instantaneous startup and shutdown, eliminating lengthy preheating phases and reducing overall energy consumption.

4.3.1. Techno-economic parameters

Technologically, modern infrared installations employ high-intensity quartz or ceramic emitters, fast-response carbon filament elements, and modular panel arrays [50]. Advanced control systems allow real-time zoning and wavelength tuning to match emitter spectra to a material's specific emissivity, further improving energy use and process uniformity. Because infrared modules are compact and combustion-free, they require minimal floor space, emit no flue gases, and obviate costly emissions treatment. Although initial capital costs can exceed those of conventional convection ovens, the productivity gains and energy savings [51], particularly in rapid-cycle or high-value processes, often justify the investment.

4.3.2. Potential applications

In practice, infrared heating has found broad uptake across food processing (blanching, baking, drying, sterilization) [52], wood drying [53], paint, plastics, glass and textiles [25]. More recently, it has been adopted for solder reflow and annealing in electronics, targeted zone heating in semiconductor manufacture, and innovative building-panel systems. Ongoing research into photonic and metamaterial emitters promises even greater spectral control and further efficiency gains.

4.4. Induction heating

Induction heating is primarily used for electrically conductive materials, especially metals, and is widely adopted in industry due to its unique advantages [54]. It generates heat directly within the workpiece in a short time, allowing precise, localized heating based on application needs. This results in efficient energy use, consistent product quality, high processing rate, and reduced material waste.

4.4.1. Techno-economic parameters

Technical advantages of induction heating include high power density that enables compact equipment and rapid heating; capability of reaching very high temperatures, up to 3000°C; localized heating of specific areas on the workpiece; precise control of heating location and intensity; suitability for automation and integration into production lines [36]. Depending on material properties, it is generally characterized by high efficiency, up to 90% [25].

4.4.2. Potential applications

However, the requirement for strong inductor–workpiece coupling imposes constraints on the size and shape of the materials that can be processed. Typical applications of induction are the

melting of metals, the heating of metals for design, brazing and welding, and all sorts of surface treatments such as hardening [55] However, by using electric conductive recipients (e.g. graphite), other materials such as glass can also be heated. Emerging uses are expanding into industries such as chemical, glass, textile, food, paper, and advanced metallurgy, including modern steelmaking [56,57]. These innovations illustrate induction heating's increasing penetration into different industry sectors driven by its precision, efficiency, and compatibility with electrified, low-carbon processes.

4.5. Resistance heating

Resistive heating technologies can be broadly categorized into direct and indirect modes, depending on whether electric current flows through the material being heated or through a resistive element that transfers heat. For this reason, applications such as resistance furnaces, resistive boilers, and electric calciners are classified as examples of the indirect heating category, while electrode boilers and direct resistive melting of materials such as glass are given as examples of direct resistive heating.

Table 5. Direct and indirect resistance heating technologies/applications

Method	Technologies
Direct	Electrode boilers, glass melting furnace
Indirect	Resistance furnace, resistance boiler, calciner, kiln.

4.5.1. Techno-economic parameters

Resistance furnaces: Electric resistance furnaces generate heat by passing current through a heating element (resistor), usually located at the walls of the furnace, that is transferred to the charge (workpiece) mainly by radiation and convection [36]. Depending on the application, we distinguish between *batch* furnaces, where charge is loaded through a door and remains still during the heat treatment process, and *continuous* furnaces, where the materials pass through a tunnel and is in continuous movement during the heating process [36]. One drawback of continuous furnaces are the heat losses that come from the openings of the furnace, especially when the belt comes outside of the tunnels. The maximum operating temperatures that can be attained by resistive heating depends on the material of the heating element: nickel–chrome alloys are used up to 1150°C, Fe–Cr–Al–Co up to 1350°C, and silicon carbide for 1400–1600°C and even over 2000°C (e.g. graphite used in vacuum) [37]. Historically, resistance furnaces, also known as indirect heating furnaces have been used for sintering, annealing, drying and other thermal processes that require temperatures between 600-1300°C [36].

Electric boilers: Electric boilers can be broadly categorized into electrode and resistance type [36]. Electrode boilers are based on direct electric heating, using three electrodes, and a neutral conductor submerged in water, where heat is generated as current passes through the water. With capacities between 5-50 MW they are usually connected to the medium voltage distribution grid (6.3-22 kV) [32]. The capital cost of electrode boilers ranges from 80-210 €/kW⁻¹ and 110-280 €/kW⁻¹, making them cost-competitive with gas boilers in certain regions. Within a similar price-range, resistance-based boilers heat water indirectly, by passing current through a heater (e.g. made from nickel-chromium), which then heats water or any other

medium using the Joule effect. Their typical capacities are 6kW-5MW, making them adequate for lower voltages (400 V or 690 V).

Glass melting: Glass is generally an electrical insulator at room temperature and remains so up to quite high temperatures. However, at very high temperatures (typically above 1000°C) glass exhibits some electrical conductivity as its viscosity decreases with temperature, ion mobility increases, and the conductivity rises. Using direct electric heating, current at 50 Hz and several thousand amperes [58] is passed directly through the glass which acts like a resistor and heats up [59]. All-electric melting requires about 760 kWh/t glass, which is a 33% more efficient than using natural gas or hydrogen [60]. The installation costs for this technology is 164 EUR/t, which is around 20% cheaper than a new gas-fired plant [24,38], but transforming existing plants to electric increase costs by 44% compared to a natural gas option and their lifetime is 7 years shorter [24,38]. As of today, there are no large-scale 100% electric melting in commercial container. Their development is somewhat hampered by the 2008 incident when Cameron Glass electrified facility lead to molten glass leakage, leading to factory closure and later bankruptcy [61,62]. The technological maturity is estimated at TRL6-7 [38,63]. While niche (electric-boost) hybrid systems are in use, their full-electric adoption remains limited and potentially applicable post-2030 [64].

Electric calciners: Electric calciners are furnaces used in the cement industry to produce quicklime and clinker. Although at relatively early development stages, electric calciners can potentially play a big role in decarbonizing cement. Today, about two thirds of the CO₂ emissions in cement production originate from the decomposition of calcium carbonate to quicklime and carbon dioxide ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) and only one third comes from the fossil fuel combustion. The decomposition of calcium carbonate occurs predominantly in the calciner and somewhat in the rotary kiln, at temperatures of 900°C and 1400°C, respectively. These temperatures are reached by the combustion of fossil fuels. The emissions from fossil fuel combustion can be reduced by electrifying the calciner and rotary kiln, assuming low-carbon electricity is used. On the other hand, CCS is necessary to eliminate the process emissions from the chemical reaction. An overview of pilot and commercial calciners and kilns for cement is given in Table 6.

Kilns: To electrify the rotary kilns, different alternatives are possible. The company Metso has developed RotarEkiln™ - an electrified kiln transforming electricity to heat using resistance heating. The kiln is designed for temperatures up to 1500°C and is 20% more efficient than traditional fuel-fired kilns [65]. VTT has also been involved in research of resistance heated rotary kilns [66] and has developed its own solution for temperatures up to 1050°C, capacities between 50-150 kg/day and a calcination degree of up to 98% [67].

4.5.2. Potential application

Resistance furnaces: Resistance furnaces are a mature technology, that has demonstrated stable and reliable operation across different industries, such a chemical, non-ferrous metals and for heat treatment of ceramics and glass.

Electric boilers: Electric boilers are mostly used for steam generation, with diverse application in the chemicals, food and beverages and textile industries [32]. As discussed in the previous section, steam represents the single largest category of industrial process heat. With a useful energy demand of 408 TWh/year, steam generation offers a significant opportunity for decarbonization through the deployment of electric boilers across the EU.

Glass melting: Direct electric heating can also be used for melting glass. Glass is thus melted at 1600°C in large constantly operating furnaces with lifetimes of about 15 years, traditionally using natural gas or coal. The combustion of fossil fuels results emissions of 0.07 – 0.16

tCO₂/tGlass depending on the fuel [63], leading to about 20 MtCO₂/year in the European Union [68]. Electrification is considered a promising solution [69] that can save about 5.5 million tCO₂/year by reducing the energy-related emissions of glass melting [64]. Being the world's largest producer of glass, the European Union needs to play an important role in decarbonizing glass manufacturing [70].

Electric calciners: Electrifying calciners in combination with CCS could reduce CO₂ process emissions up to 78% [71]. However, although they enhance process efficiency compared to fossil fuelled calciners by approximately 10%, their capital costs are markedly higher—193% more for a new plant and 190% more for a refurbishment [24]. Investment expenditures amount to roughly 252€/t of clinker for new build and about 157 €/t of clinker for refurbishment [38]. Different electrification routes are technically possible for calciners, among which microwave and induction heating. The most promising solutions being developed leverage direct resistive heating [72] and electric arc heating [3]. For instance, to produce 1 Mt clinker per year, the electrical capacity of the resistively heated calciner is estimated to be 85 MW [72]. The ECoClay partnership, led by FLSmidth and including DTU, Rondo Energy, Vicat, and Cementos Argos, is developing a system for fully electrified clay calcination, based on a resistively heated flash calciner [73]. A dynamic model of the electrified plant reveals its potential for smart integration in the power sector and enables an evaluation of its demand response potential [74].

Table 6. Pilot and commercial electric calciners and kilns for the cement industry

	Technology	Temp. (°C)	Status	Ref.
FLSmidth ECoClay™	Electric flash calciner	~900	Pilot	[73]
SaltX EAC	Electric arc calciner	~900	Pilot	[75]
Coolbrook RDH™	Electric rotary kiln	<1700	Pilot	[76]
Metso RotarEkiln™	Electric rotary kiln	<1500	Commercial	[65]
VTT	Electric rotary kiln	1050	Pilot tested	[67]

In parallel, efforts to decarbonize the alumina industry have begun to explore the use of electric drop tube flash calciners [77]. These systems eliminate the use of fossil fuels, enabling the reduction of Scope 1 emissions, and offer potential synergies with renewable electricity. Additionally, electric calciners can enhance process integration: the absence of an internal combustion source allows for recovery of high-purity steam, which can be recycled into the Bayer process via thermal or mechanical vapor recompression, improving overall energy efficiency [77].

Kilns: Electric kiln can be used for lime production, which is a necessary element for pulp and cement production [66]. Previous research argues that cost parity for electric kilns requires electricity prices to be below approximately €18.70/MWh [78], implying that either investment subsidies or reduced electricity tariffs are necessary. Potential improvement of their economic viability may require looking into additional revenue stream, such as providing ancillary services in electricity markets [79]. However, electrification in the cement industry is still not widely economically viable, as it is competing with alternative decarbonization approaches such as biomass and waste as alternative fuels [38], indirect electrification via hydrogen, hybrid approaches and post-combustion CO₂ capture [80].

4.6. Electric arc heating

Electric arc heating involves the generation of heat through one or more electric arcs formed between the tips of electrodes and the charge material. It is a widely used thermal technique applied in various industrial processes, where localized heat is generated by electric arcs to join, shape, or modify materials. The most common application of arc heating are electric arc furnaces (EAFs), which are the main focus of this subsection [81]. The main application of EAF is found in the production of secondary steel, i.e. turning ferrous scrap into molten steel that can later be cast and rolled. In the process, metal scraps and limestone are fed as charge in the EAF and the electrodes are lowered toward the charge to initiate an electric arc, and brief contact can occur, however sustained direct contact is avoided because it causes an undesirable short circuit. Electrical current is passed through the electrodes and heat is produced by the electric arcs that occur between the electrodes and the charge.

4.6.1. Techno-economic parameters

Reaching temperatures up to 1800°C, most heat is transferred by radiation, while smaller portions are transferred via convection and conduction [36]. The first patent for an EAF, which dates back to 1898, was followed by multiple design adjustment that led to a reduction of their electricity consumption – from 580-650 kWh/t steel to 320-350 kWh/t steel – and material use – electrode consumption reduced 4-5 times since 1970s [36]. The overall power-to-heat conversion efficiency of EAF ranges between 0.65 and 0.95 [36,37], depending on the operational setting. The typical unit sizes are 10-200 MVA [25]. The IEA estimates an annualized investment cost for secondary steel production using an EAF between 34-58 \$/t steel [82].

4.6.2. Potential applications

Main application of electric arc heating involved arc welding, metal cutting, and surface treatment and EAFs. In While Lopez et al. expect that steel recycling using EAFs will be the dominant steel production route in the future [83], EAFs can also be used for primary steel production [84]. This is achieved by feeding reduced iron ore, also known as iron sponge, into the EAF to produce molten crude steel. The chemical reduction of the iron ore is typically done using natural gas. The annualized investment cost for this route, referred to as DRI-EAF, are between 53-137 \$/t crude steel [82]. Assuming low-carbon electricity is used for the EAF, most emissions in this production route come from the combustion of natural gas for the reduction of iron.

If natural gas is substituted with green hydrogen, however, there is significant potential to eliminate fuel-related emissions [85] (H₂-DRI-EAF). Leveraging Sweden's low emissions and low cost electricity, this method is already tested as part of the HYBRIT venture established between SSAB, LKAB and Vattenfall [86]. While H₂-DRI-EAF can become cost competitive by 2035 [83], its production cost are currently +36–61% [87] or +33–117% [88] higher than standard methods, as reviewed by Diesing et al. [89]. Nevertheless, it is a promising alternative to current practices, in one of the most challenging sectors for decarbonisation.

4.7. Plasma heating

Plasma heating generates thermal energy through the ionization of process gases via an electric arc or radiofrequency field. Under intense electrical excitation, atoms in the gas dissociate into ions and free electrons, forming a high-temperature plasma that can exceed 5 000 °C. Heat transfer occurs predominantly through radiative emission and convective flow within the plasma plume, enabling rapid and localized energy delivery.

4.7.1. Techno-economic parameters

Plasma torches are high-temperature electric heating devices that operate by ionizing a process gas using an electric arc to create a thermal plasma with temperatures even beyond 5000 °C [90]. Their efficiency ranges from 0.5 to 0.9, depending on the configuration, gas composition, and heat recovery method [25]. While they offer rapid and localized heat delivery, a major limitation is their short electrode lifetime, typically around 2000 operational hours. Although plasma torches remain capital- and maintenance-intensive, their modularity, extremely high thermal potential, and compatibility with renewable electricity position them as a long-term option for electrifying hard-to-abate processes. Continued research into longer-lasting electrode systems, stable arc control, and more efficient power supplies is essential to reducing cost barriers and improving industrial viability.

4.7.2. Potential applications

They have several applications in mechanical, chemical and steel industry, including cutting, welding, surface treatment [91]. Cutting and surface treatment, in particular, are standard uses of plasma torches in today's industry. Recent developments are directed towards the application of plasma heating in the steel [92] and cement industry [90]. For example, an Unlike resistance heated calciners, SaltX [75] has developed its Electric Arc Furnace, which essentially utilizes plasma heating for cement production, and is set to be piloted in partnership with thyssenkrupp Polysius [93].

4.8. High-temperature thermal storage

High-temperature thermal energy storage (HT-TES) systems convert electricity into heat, store it, and discharge it as thermal and/or electrical energy on demand [94]. They are considered a favourable technology for industrial decarbonization, as they combine relatively low cost, high efficiency and operational flexibility.

4.8.1. Techno-economic parameters

There is significant uncertainty about actual investment cost data due to the fact that the technology is still at early stages of commercialization. Industry insights reveal that costs (including manufacturing and installation) currently range from 85–210 \$/kWh, with projections falling to 40–110 \$/kWh by 2030, and potentially 20–55 \$/kWh by 2035 [95], as shown in Figure 6. According to estimates from the Danish Energy Agency [41], the capital expenditures for rock-based thermal storage systems are approximately 120.4 €/kW for charging (ranging from 40.3 to 167.0 €/kW), 30.1 €/kW for discharging (10.1–41.8 €/kW), and 13 €/kWh for storage capacity (4.4–18.1 €/kWh). In comparison, molten salt systems exhibit a wider range of capacity-related CAPEX (31–109 €/kWh) and fixed OPEX typically amounting to 0.5–3% of CAPEX per year.

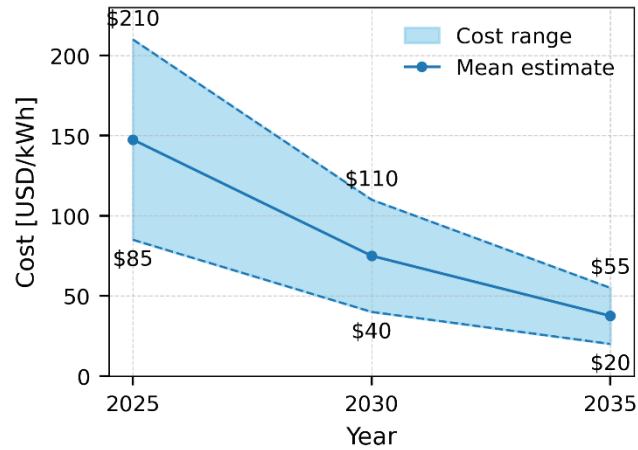


Figure 6. Projected thermal battery costs (own illustration based on [95])

The temperature spectrum of HT-TES, ranging from 300 °C to over 2400 °C, depends on the electrothermal conversion method and the storage medium. In terms of deployment, HT-TES solutions are often modular, ranging from 1-1000 MWh, as shown in Table 7.

Three heating methods underpin most current HT-TES systems. First, direct resistive (Joule) heating of conductive materials, as used in Electrified Thermal Solutions' JouleHive [96], which can reach ultra-high temperatures (up to 1800 °C) and demonstrates round-trip efficiencies exceeding 90%. This method is technically more complex and is based on the direct passage of electric current through chemically doped firebricks [97], which act as both heater and storage medium. The second, simpler method is indirect resistive heating, which is employed by companies like Rondo [98], Kraftblock [99], and Brenmiller [100]. These systems use electric heaters to transfer heat to surrounding media via conduction and convection. A third approach is used by Antora [101], which applies resistive heating but stores thermal energy in graphite blocks that are heated by radiation. As the carbon blocks radiate energy and light due to their high temperatures (up to 2400 °C), innovative thermal photovoltaic conversion is used to produce electricity as well [102].

The storage media used in HT-TES systems also vary significantly. Antora uses graphite block due to its high-temperature stability and conductivity. Others such as Rondo use refractory bricks, while Kraftblock use granular composites produced from 85% upcycled blast furnace slag. Sand is utilized by Polar Night Energy for its availability and cost-effectiveness. Molten salts are used by Kyoto Group, Saltes and Malta Inc, while 1414 Degrees store energy in molten silicon as latent heat. These systems generally achieve round-trip efficiencies between 60% and 93%, with thermal losses typically below 1% per hour and insulation limiting daily heat leakage to less than 3%.

4.8.2. Potential applications

In the short term, HT-TES is expected to be deployed primarily in mid-temperature industrial steam applications, where they can be integrated with existing gas boiler infrastructure [25]. Over time, higher-temperature applications such as cement, steel, and ceramics processing may also become viable. Currently, many established global companies are piloting these technologies, among which are PepsiCo, Ferrero Group, Philip Morris, Calgren Renewable Fuels, Diageo, Eastman, Covestro and Greenlab, as the results seem promising.

For a storage system using refractory bricks, simulations using Crank–Nicolson finite difference schemes indicate that systems in the 100–1000 MWh range can cycle daily, delivering 70–90% of their thermal capacity with minimal losses. They demonstrate compelling

economics, with levelized heat costs as low as \$10/kWh and payback periods under two years in certain U.S. regions [39]. Global modelling suggests that widespread deployment of HT-TES could lower 2050 battery capacity by 14.5%, hydrogen production for electricity by 31%, and annual energy system costs by nearly 2% [40]

But despite its merits, this emerging sector is not without its challenges. For instance, Brenmiller, one of the most mature companies, reports ongoing financial losses and acknowledges significant risks to long-term profitability under current conditions. These challenges stem from a combination of factors, including reliance on third-party manufacturers, difficulties in retaining skilled personnel, fragmented regulatory environments across countries, evolving environmental legislation, limited access to capital, and barriers to securing intellectual property rights for their core technologies [100].

Table 7. Examples of high-temperature thermal energy storage systems with a commercial or pilot status

Company (Country)	Industry sector	Core technology	Temp (°C)	Deployment scale and model	Status	Technical data	Ref.
Antora Energy (USA)	Paper, food, concrete, chemicals, steel, cement, ceramics, glass.	Graphite blocks; High-efficiency thermal photovoltaic conversion	2400	Full-scale pilot in Fresno, CA; HEATCORE module: available in 2025, Higher temp. products in development.	TRL 7	HEATCORE: 100-400 °C, ~2.65 MWth/m ² , ~97%; ~50 h storage	[101, 102]
Electrified Thermal Solutions, (USA)	Cement, steel, chemicals	Ceramic bricks (Electrically conductive “E-Bricks”)	1800	Joule Hive, Commercial-scale pilot at SWRI (2024–25)	TRL 7	Resistance heating to 1800 °C; DOE-funded \$5 M+ pilot; target ~60% round-trip efficiency; designed for continuous steam delivery	[96]
1414 Degrees (Australia)	Industrial process heat	Silicon PCM	1414	SiBrick®, SiBox® Demonstration Module tested for 1 year and 230 cycles, maintained stable temperature up to 900°C 1 MWh demo furnace; 75 MWh planned pilot (2025)	TRL 7–8	Molten silicon latent heat ~0.5 MJ/kg; continuous dispatch;	[103]
Kraftblock (Germany)	Paper, food, concrete, chemicals, glass, ceramics	Granules produced from 85% upcycled blast furnace	1300	Multiple modular projects installed. In development: 25 MWth gas boiler replaced by 70 MWth storage for chips frying in PepsiCo factory	TRL 8	PepsiCo site (in development): 175 MWh (5x35 MWh), ~300 °C, 4.5 MWeI charge, 4.5	[99, 104]

		slag; Proprietary binding agent.				MWth discharge, >95% efficiency.	
Rondo Energy (USA)	Paper, food, concrete, chemicals, steel, cement, ceramics, glass.	Refractory bricks (Alumina– silica)	1100	Established clients: Calgren Renewable Fuels, Diageo, Eastman, Covestro, Greenlab, Siam Cement Group. HaaS model (no upfront CAPEX)	TRL9	RHB100: 100 MWh, 7 MWth, 20 MWac, 98%, 15x12x12 m. RHB300: 300 MWh, 20 MWth, 70 MWac, 98%, 40x15x12 m.	[98]
Polar Night Energy (Finland)	Pulp and paper, food, textiles, chemicals, metals, manufacturing	Crushed stone (sand)	600	4 Sand Battery projects completed in Hiedanranta, Vatajankoski and Loviisan Lämpö pilots for district heating. €7.6 million secured in seed funding in 2024. Models: Sand Battery 2 MW and 10 MW	TRL 9	Sand Battery 2 MWth: 200 MWh 85% roundtrip eff., 15x12 m; Sand Battery 10 MWth: 1000 MWh 90% roundtip eff., 30x12 m	[105]
Lumenion (Germany)	District heating, food, paper, chemicals	Steel bars	650	2.4 MWh pilot (Berlin, 2019); 20 MWh under construction	TRL 8	20 MWh unit in Friedrichsgabekoog: 5 MWel, saturated steam at 17 bar, ~95% efficiency	[94]
Brenmiller Energy (Israel)	Pulp and paper, food, textile and chemicals	Crushed volcanic rock (bGen)	650	Enel Italy: 24 MWh; Philip Morris Romania: 31.5 MWh; Fortlev Brazil: 1 MWh biomass-charged TES; Hungary PPF: planned 30 MWh; TEMPO 32 MWh	TRL 8-9	Modular: 100-500 MWh, 1-100 MWel charging; 2-200 ton/h steam, 1-90 bar; 97% efficiency, 100-530 °C, 0.1%/h heat loss, 330 kWh/m ³	[100]

Malta Inc. (USA/Spain)	Grid-scale power & heat	Molten salt	565	14 MWh demo (Puertollano, 2025)	TRL 7-8	Steam-boosted heat pump: COP ~1.6; dual heat/power; CAPEX ~\$500/kWh; round-trip efficiency 60-65%	[94,106]
Magaldi Green Energy (Italy)	Pulp and paper, food, textile and chemicals	Fluidized silica sand bed (MGTES)	400	Ferrero Group Pilot: 5 MW PV plant + 13 MWh storage at 120-400 °C	TRL 7	Modular: 5-100 MWh units; 1-20 MWth discharge, hours to weeks storage, >90% capacity, 2%/day loss, 400 kWh/m ²	[94,107]
Saltes (Netherlands)	Pulp and paper, chemicals, textiles	Molten salt	400	Successor of Brabetech MW-scale pilot (“ThermalPod”)	TRL 6	Multi-day storage (up to 1 week); heat output to 350 °C; thermal loss ~2%/day	[94,108]
Kyoto Group (Norway)	food and beverage, pharmaceuticals, chemicals, manufacturing, and heavy industry.	Molten salt	300	Heatcube product: 39 -104 MWh. Heat-as-a-service and Heat-as-a-product models available. KALL Ingredients Kft: HaaS signed in 2023. Norbis Park Heatcube: Battery-as-a-service model.	TRL 8-9	10-20 MWac charge, <104 MWh, <14 MWth discharge, 3-25 bar, 150-300°C, >93% roundtrip efficiency, response time: <3 s (charge), <300 s (discharge)	[109]

5. DISCUSSION

As industrial electric heating technologies continue to emerge, it is important to accurately plan for their strategic deployment. Detailed bottom-up models, such as the FORECAST model [110], or IndustryPLAN [111], demonstrate the value of subsectoral process modelling. Such models capture energy efficiency or fuel-switching options based on plant-level specific, investment cycles and spatial deployment with high fidelity [112]. Yet their national-scale granularity often comes at the expense of system-wide interactions. By combining spatially and temperature-resolved heat maps with integrated energy system models, planners can bridge this gap: they retain the nuanced technology-sector mappings from subsector studies while embedding them in a broader context that links industry with electricity, heating and transport infrastructures [113]. Accurate representation of direct electrification technologies in these models, reflecting real-world efficiencies, load flexibility and cost trajectories, ensures that scenario analyses reflect both the detailed potential of heat pumps, electric boilers, plasma torches and high-temperature TES and the emergent behaviours of the power system. The result of this work is a dataset that provides modellers with a techno-economic data, demand projections and robust applicability overview (Table 8), enabling more realistic least-cost pathways, infrastructure planning and policy evaluation. It is especially relevant for sector-coupled energy system models, such as PyPSA [114], H2RES [115], Euro-Caliopé [116], EnergyPLAN [117], LUT model [23] and DIETER [118,119], and can contribute to cross-model alignment of input data.

For example, models that include heat pumps and electric boilers in food, chemicals and pulp & paper, alongside emerging options like plasma torches or HT-TES for ceramics and machinery can better quantify the trade-offs between electrification, biomass use and hydrogen. Integrating these technology-sector considerations into optimization frameworks allows assessment of regional investment needs, grid reinforcement requirements and storage deployment.

Table 8. Applicability matrix of industrial heat electrification technologies and applications

	FBT	CHE	PPA	ISE	CEM	NFM	GCER	WWP	TEX	TRE	MCH
Heat Pump	●	●	●	◐	●	◐	◐	◐	●	●	◐
Elec. Boil.	●	●	●	◐	●	●	◐	●	●	●	●
Resis. Furnace	○	○	○	○	●	●	●	○	○	●	●
Electric calciner/kiln	○	○	◐	○	◐	◐	●	○	○	○	○
Dielectric heating	●	◐	◐	○	○	○	●	●	●	○	○
Infrared heating	●	●	●	○	○	○	●	●	●	●	●
Induction heating	○	○	○	●	○	●	○	○	○	●	●
Electric arc heating	○	○	○	●	○	●	○	○	○	○	○
Plasma heating	○	○	○	◐	○	○	◐	○	○	●	●
HT-TES	●	●	●	○	◐	◐	◐	○	●	◐	◐

FBT – food, beverages and tobacco; CHE – chemical industry; PPA – pulp and paper; ISE – iron and steel; CEM – cement; NFM – non-ferrous metals; GCER – Glass and ceramics; WWP – wood and wood products; TEX – textiles; TRE – transport equipment; MCH – machinery equipment; Applicability: ● -high; ● - medium; ○ – low.

The decarbonization of industrial process heat is set to become a central pillar of the EU’s climate and industrial policy agenda. Regulatory signals, notably the Clean Industrial Deal [120] and the Innovation Fund’s pilot heat auction [27], have already defined strategic priorities, particularly by introducing a temperature-based structure to guide funding support. The IF25 allocated €1 billion equally across two bands: 100–400 °C and >400 °C. This explicit segmentation of temperature bands provided a clear framework for identifying both mature electrification opportunities and emerging high-temperature decarbonization pathways. A overview of the maturity of various technologies is given in Table 9.

Table 9. Technology readiness of industrial heat electrification technologies and applications [25,121]

Technology/App lication	Readiness	Comment
Heat Pump	TRL 8-9	Available today, lower TRLs for higher temperatures.
Electric boilers	TRL 9	Mature and commercially available. Commonly used for steam generation.
Resistance Furnace	TRL 9	Mature and established technology, commercially available in multiple industries.
Calcliner, kiln, furnace	TRL 6-9	Emerging technology at pilot or early commercialization stage for cement and steel.
Dielectric heating	TRL 9	Mature and well established in drying and curing in food processing and plastics.
Infrared heating	TRL 9	Mature and well established, applicable in multiple industries, limited scale.
Induction heating	TRL 8-9	Established for metal hardening, forging, welding, emerging in furnace pre-heating
Electric arc heating	TRL 9	Widely deployed for steel production; mature and proven.
Plasma heating	TRL 7-9	Emerging for high-temperature needs; pilot/commercial deployment pending; technical maturity growing.
Thermal storage	TRL 6-9	Deployed at industrial scale in specific contexts; mature for lower temperatures; scaling for high-temperature applications in progress.

Motivated by the temperature band segmentation of IF25, our analysis maps the potential market for electrified industrial heat across the EU27. In 2021, approximately 1 040 TWh of useful energy was consumed for process heat, with around 42% falling within the sub-400 °C range (437 TWh). This demand is largely concentrated in sectors such as food, pulp and paper, and chemicals, together accounting for roughly 646 TWh of heat demand across all temperature

bands. However, sub-400 °C heat demand is well suited to established technologies, including industrial heat pumps, electric boilers, resistive heaters, and thermal energy storage systems Figure 7. Assuming an average utilisation rate of 80% and that 30% of the sub-400 °C heat demand is supplied by industrial heat pumps, the full direct electrification of this segment would require an installed electrical capacity of roughly 50 GW and an additional 350 TWh of annual electricity consumption — comparable to Italy’s total electricity use. Although this is a very rough estimation, the sheer magnitude reveals the need for coordinated planning between industrial decarbonisation policies and power system development. Heat demand above 400 °C remains dominant in energy-intensive sectors such as cement, primary steel, non-ferrous metals, and ceramics. In these domains, our technology mapping identifies electric arc furnaces and induction heating as established solutions, while plasma heating, and high-temperature thermal energy storage are emerging as viable options.

By triangulating the process heat temperature distribution, the IF25 funding architecture, and the current state of technological readiness, it becomes evident that the policy framework is well-calibrated to support near-term deployment of mature solutions and incentivize medium-term innovation for high-temperature applications. Projects funded under IF25 are required to demonstrate cost-effective CO₂ abatement, quantified in subsidy per tonne avoided, and are stimulated to permanently displace fossil-based heat capacity. Furthermore, technologies are eligible to be funded if they have a high utilisation rate ($\geq 80\%$ of annual hours) or demonstrated operational flexibility. These criteria implicitly favour the integration of thermal storage and smart demand-side management, which can also reduce peak electricity system stress. However, funding incentives alone are not enough and should be supplemented with a EU-wide industry electrification strategy, enhanced funding streams, enabling carbon pricing mechanisms, tax and levy reforms and addressing grid infrastructure bottlenecks, among others [122]. A right mix of industrial decarbonization policies have delivered positive outcomes in the past and should also be deployed in the context of direct electrification of industry [123].

Moreover, strategic electrification of low-to-medium temperature heat enables targeted fuel switching. Specifically, scarce decarbonization resources such as sustainable biomass can be reserved for high-temperature processes that lack cost-effective electric alternatives. This allocation strategy optimizes the impact of clean energy vectors and supports a more rational, system-integrated transition for the industrial sector.

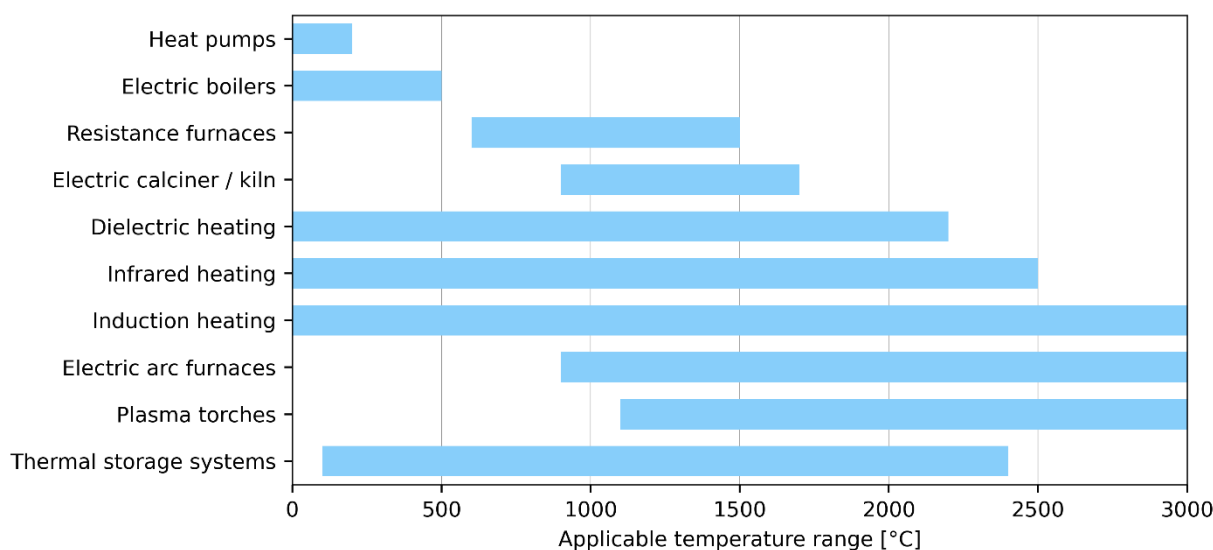


Figure 7. Temperatures of electric heating technologies and applications (inspired by [25])

5.1. Limitations and future research directions

Despite its aim to enable comprehensive assessment of the heat demand and the technologies applicable across sectors, this study is subject to several limitations. First, the methodology relies on the JRC-IDEES dataset, which, despite its granularity, may still include uncertainties in sectoral disaggregation and process mapping. Second, techno-economic data for power-to-heat technologies are compiled from heterogeneous sources, and while harmonized where possible, they reflect a combination of pilot, commercial, and prototype stages. To ensure better congruency of the dataset, certain technologies, such as Coolbrook's RotoDynamic Heater™ were not integrated in the analysis, as it is based on electromechanical heat generation [76]. Third, the time-series data derived from Hotmaps rely on representative days, which may not fully capture intra-annual variability or sector-specific seasonality. These limitations may affect the precision of the results and their applicability to highly granular, site-specific studies, but they do not diminish the dataset's relevance for strategic, system-level analyses and technology deployment planning.

There are multiple research directions from this point onwards, that can leverage the findings of this work or fill identified gaps:

- Extend energy-system models to jointly optimize industrial investments alongside those in electricity, heating, and transport, enabling the assessment of cross-sector synergies and potential trade-offs. Transition pathways in the industry sector are often exogenously defined in energy system models. Future works can ensure more models incorporate the results of this study to enable endogenous decarbonization decision, taking into account sector coupling with adjacent systems such as district heating networks, waste-heat reuse and synthetic fuel production.
- Integrate geospatial analysis to identify industrial clusters with high electrification potential and assess requirements for grid reinforcement, local renewables and storage. Embed dynamic demand-response algorithms to evaluate how industrial process flexibility can provide ancillary services and mitigate peak stresses on the power system.
- Techno-economic case studies of each electrification technology across key industrial branches to capture real-world performance, learning-curve effects and site-specific cost variances can be conducted to reveal site- and industry-specific cost effectiveness of electrification. These studies can focus on co-investing in on-site renewable energy sources and energy storage systems, or assess the impact of different policy measures, such as carbon taxes, power-purchase agreements, investment subsidies etc.
- Model the influence of carbon pricing, subsidies and regulatory differentials on the geographical relocation of energy-intensive facilities. Analyze how relocation trends affect national and regional decarbonization trajectories, supply-chain resilience and policy effectiveness.
- Extend heat demand mapping to Southeast European countries, which are currently not included in the JRC-IDEES dataset.

6. CONCLUSION

The decarbonization of industrial process heat is an important yet often underestimated challenge in the European Union's pursuit of climate neutrality. This work addresses critical data gaps by providing a comprehensive, spatially and sectorally resolved dataset of industrial

heat demand across the EU27. Our analysis, based on the JRC-IDEES-2021 framework, reveals that the conventional focus on high-temperature "hard-to-abate" sectors, while important, overlooks the substantial decarbonization potential in low- and medium-temperature applications. Nearly half of the EU's total industrial energy demand is concentrated in the pulp and paper, chemicals, and food industries, with approximately two-thirds of their heat requirements falling below 400°C. This finding challenges the prevailing narrative that decarbonization is primarily a high-temperature problem and underscores the immediate opportunity for electrification via mature power-to-heat technologies.

The harmonized dataset and review of techno-economic parameters for a range of electrification technologies provide a crucial resource for energy system modellers and policymakers. By linking specific heat demand profiles to viable technological solutions, this work enables a more accurate and granular representation of industrial decarbonization pathways. This is essential for moving beyond a one-size-fits-all approach to policy and for designing targeted interventions that align with national and regional industrial characteristics. For instance, countries like Sweden and Finland, with significant pulp and paper sectors, show a high potential for near-term electrification due to their predominantly low- to medium-temperature heat requirements.

In essence, our study offers a dual contribution: first, a quantitative re-evaluation of the industrial heat landscape in Europe, and second, a practical toolkit for integrating industrial electrification into long-term energy planning models. The transition from a fossil-based to an electrified industrial system will require not only technological innovation but also a concerted effort to optimize infrastructure, policy, and data availability. The analysis and insights presented here are designed to support this effort, helping to bridge the gap between high-level climate ambitions and the on-the-ground technical realities of industrial decarbonization.

Author contributions

V.Z.G: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft. **S.C:** Conceptualization, Investigation, Formal analysis, Writing – reviewing and editing. **N.M:** Methodology, Validation, Writing – reviewing and editing. **N.D:** Conceptualization, Supervision, Validation.

ABBREVIATIONS

Abbreviation	Meaning
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CHE	Chemical industry
CO ₂	Carbon dioxide
COP	Coefficient of performance
CEM	Cement
DH	District heating
EAF	Electric arc furnace
EU	European Union
EU27	European Union (27 Member States)
FBT	Food, beverages and tobacco
GCER	Glass and ceramics

HT-TES	High-temperature thermal energy storage
IF25	Innovation Fund 2025 pilot heat auction
ISE	Iron and steel
JRC	Joint Research Centre (European Commission)
JRC-IDEES	Joint Research Centre – Integrated Database of the European Energy System
LUT	LUT Energy System Model
MCH	Machinery equipment
MW	Megawatt
MWh	Megawatt-hour
NFM	Non-ferrous metals
O&M	Operation and maintenance
PPA	Pulp and paper
PV	Photovoltaic
R&D	Research and development
TES	Thermal energy storage
TRL	Technology readiness level
TRE	Transport equipment
TWh	Terawatt-hour
WWP	Wood and wood products

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APPENDIX

Table A.1. Mapping of useful energy demand across different industrial processes

	Electric other	Electric thermal	<100°C	100–400°C	400–1000°C	>1000°C
Primary steel	• General appliances & machinery • Casting • Refining & rolling	• Low-enthalpy heat	• Low-enthalpy heat	• Steam processing	• Smelters • Finishing thermal treatments, e.g. annealing	• Sinter/pellet making • Re-heating furnaces • Blast furnace
Secondary steel	• General appliances & machinery • Product finishing • Furnaces, refining and rolling	• Low-enthalpy heat	• Low-enthalpy heat	-	• Smelters • Thermal product finishing	• EAF – fuels and reducing agents • Refining.
Alumina, primary aluminium	• General appliances & machinery • Alumina refining • Aluminium processing	• Low-enthalpy heat • Smelting • Aluminium finishing	• Low-enthalpy heat	• Alumina refining, thermal processing • Steam	• Aluminium thermal finishing	-
Secondary aluminium	• General appliances & machinery • Aluminium processing and finishing	• Low-enthalpy heat • Pre-treatment, remelting	• Low-enthalpy heat	• Aluminium thermal processing • Steam processing	• Pre-treatment, remelting • Aluminium thermal finishing	-
Other non-ferrous metals	• General appliances & machinery	• Low-enthalpy heat • Metal production, processing and finishing	• Low-enthalpy heat	• Steam processing	• Thermal metal finishing	• Thermal metal production and processing

Chemical industry - Basic chemicals	• General appliances & machinery • Generic electric processes	• Low-enthalpy heat • Electric furnaces • Process cooling	• Low-enthalpy heat • Process cooling	• Steam processing	• Thermal furnaces	-
Non-metalic mineral - Cement	• General appliances & machinery • Grinding, milling, packaging, precasting	• Low-enthalpy heat	• Low-enthalpy heat	-	• Pre-heating and calcination	• Kilns and clinker production
Non-metalic mineral - Ceramics	• General appliances & machinery	• Microwave drying and sintering • Electric kilns and furnaces	• Low-enthalpy heat	• Steam processing	• Thermal drying and sintering	• Kilns and furnaces
Non-metalic mineral - Glass	• General appliances & machinery • Glass forming and finishing processes	• Low-enthalpy heat • Melting • Annealing	• Low-enthalpy heat	-	• Thermal annealing	• Thermal malting tank
Pulp and paper	• General appliances & machinery • Wood preparation, grinding • Pulping, cleaning • Product finishing • Electric paper machines	• Low-enthalpy heat	• Low-enthalpy heat • Thermal pulping • Stock preparation	• Steam processing	• Calcination	-
Food and tobacco	• General appliances & machinery	• Low-enthalpy heat • Direct and process heat (electric and microwave) • Drying, cooling	• Low-enthalpy heat • Thermal process heat	• Direct heat • Steam processing	-	-
Transport equipment	• General appliances & machinery • Product finishing	• Low-enthalpy heat • Heat treatment • Electric connections	• Low-enthalpy heat • Thermal heat treatment	• Steam processing and drying	• -	• Welding, thermal connection • Foundries

		• Electric foundries				
Machinery equipment	• General appliances & machinery • Product finishing	• Low-enthalpy heat • Electric heat treatment, connections and foundries	• Low-enthalpy heat	• Steam processing	• Thermal heat treatment	• Welding, thermal connection • Foundries
Textiles and leather	• General appliances & machinery	• Low-enthalpy heat • Electric and microwave drying	• Low-enthalpy heat	• Steam processing	-	-
Wood and wood products	• General appliances & machinery	• Low-enthalpy heat • Mechanical processes	• Low-enthalpy heat	• Steam processing	-	-

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