



# Industrial Power-to-Heat: Enabling Circularity in Energy Systems

**Unpacking the cross-sectoral, innovation opportunities for Ireland**

A CIRCULÉIRE 2025 Circular Economy Guide developed by Irish Manufacturing Research



An Roinn Aeráide,  
Fuinnimh agus Comhshaoil  
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## About CIRCULÉIRE

CIRCULÉIRE, the National Platform for Circular Manufacturing seeks to accelerate Ireland's transition towards a net-zero carbon circular economy. A key objective of the programme is to demystify, de-risk and deliver circular business model innovation for Irish industry.

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# Executive Summary

**Ireland is rapidly increasing renewable electricity, yet a sizeable share is still being curtailed or dispatched down, while industrial heat remains overwhelmingly fossil based. Power to Heat (P2H), combined with thermal storage and smart control, can revalorise surplus renewable electricity into useful heat, cutting emissions, easing grid constraints, and improving energy efficiency in line with circular economy principles.**

## **Ireland's Energy Landscape and the Heat Decarbonisation Challenge**

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Ireland is rapidly expanding its renewable electricity generation, driven by ambitious Climate Action Plan targets, including 80% renewable electricity by 2030. Wind and solar capacity are high and increasing, with growing contributions from battery storage and flexible demand across industry and commerce.

However, a significant share of renewable electricity continues to be curtailed due to system constraints. In 2023, over 10% of available wind energy was dispatched down. And, while some producers export surplus electricity, this is not always feasible or financially attractive, highlighting the importance of maximising local, onsite use of clean power.

At the same time, heat remains a major decarbonisation gap. It accounted for over 38% of Ireland's energy-related CO<sub>2</sub> emissions in 2023, and more than 90% of heat is still fossil-fuel-based. Industry alone uses over a third of the country's total heat. In turn, heat represents around two-thirds of industrial emissions. High-temperature processes dominate many sectors, meaning no single solution fits all: a range of different technologies is needed.

The use of renewable electricity to generate heat, particularly through technologies like heat pumps and other Power-to-Heat solutions, is growing. Capturing excess renewable electricity and converting it into useful heat, especially in industrial settings, offers a promising pathway to reduce emissions, cut curtailment, and improve energy resilience. When combined with thermal storage, these solutions also add operational flexibility by allowing heat to be stored and used when needed. Together, they offer a meaningful opportunity to achieving Ireland's decarbonisation targets.

## **Why Power-to-Heat (P2H) and storage matter**

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Converting surplus or low-cost renewable electricity into heat and storing it for later use helps to minimise energy waste, improve resource efficiency, and enhance system flexibility, aligning closely with circular economy principles.

For companies generating their own renewable electricity, especially where market price differences and export limitations apply, Power-to-Heat offers a way to use that electricity in a high-impact, productive manner, by displacing fossil-based thermal demand. Instead of letting excess electricity go unused or exporting it at low value, it can be redirected to meet on-site heat needs,

improving both energy efficiency and carbon performance.

In addition, Power-to-Heat solutions offer additional system value by reducing curtailment, lowering reliance on imported fuels, cutting operating costs, and enabling demand-side flexibility that supports both decarbonisation and grid stability, benefits that are further enhanced when combined with thermal storage.

## Technology landscape

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A broad portfolio of mature and emerging electric heat technologies exists, covering from low to high temperature needs. The report classifies them by the physical mechanism of heat delivery and maps them to industrial processes and temperature grades. No single technology solves all use cases; optimal stacks pair efficient electric heat technologies with storage and smart controls.

The guide presents seven Power-to-Heat production technologies with dedicated analysis, each suited to specific industrial heat demands by temperature, application, and process type:

- **Resistance Heating:** A mature and widely used method for generating medium- to high-temperature heat. Offers straightforward integration and fast response times, making it compatible with variable renewable electricity. It can also be easily integrated with a thermal storage system. Electric boilers are a very well-known and widely applied example of a solution that relies on resistance heating technology.
- **Induction Heating:** Efficient and precise heating for electrically
- conductive materials, with the ability to achieve very high temperatures. Common in metalworking industries for processes like forging, hardening, or melting.
- **Infrared Heating:** Suitable for surface heating and drying applications. Provides rapid, targeted heat transfer without the need for contact.
- **Dielectric Heating (Microwave and RF):** Enables volumetric heating of non-conductive materials, such as food or plastics. Valuable for drying, curing, or pasteurising, particularly in niche or controlled applications.
- **Heat Pumps:** Highly efficient for low- to medium-temperature processes. Can be integrated into indirect heating systems and combined with storage. Particularly suitable for steady, long duration loads.
- **Electric Arc Furnaces (EAF):** High-temperature technology primarily used in steel recycling and production. Already widespread in the metals sector.
- **Plasma Heating:** An advanced, high-temperature option capable of exceeding 3,000°C. Still niche in industrial use, but suitable for extreme heat applications.

Similarly, a guide for Heat storage technologies is also included in the report with an analysis for most suited technology application:

- **Sensible Heat Storage:** Most common heat storage method, using a liquid or solid medium to store the heat. Liquids typically consist of water, mineral and synthetic oils, and molten solar salt. Solids include concrete, steel, sand, or crushed rocks.

- **Latent Heat Storage:** Typically uses materials which store and release heat through a phase change. The current commercial materials are best suited for low to medium temperature grades.
- **Thermochemical Heat Storage:** A similar form of heat storage, differing by being driven via endothermic reactions. The heat is recovered when the reaction is reversed. The reaction has the advantage of high energy density and long-term storage without thermal losses. However, the technology is not commercial yet, due to complexity of the process and technology.

## Main Conclusions

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### **Heat Electrification is ready for uptake:**

The technology for electrifying industrial heat is already technically and commercially viable. Demonstrated across case studies, industrial heat bears significant energy and cost saving opportunities when upgrading from the traditional heating processes. Across the heat grades, high grade heat has proven the most complex to electrify.

**Ready to deploy:** A variety of heat electrification technologies are ready for deployment yet are limited by the industry's familiarity with the technologies. Proven technologies like industrial heat pumps can replace <150°C boilers; electric arc and induction furnaces can replace blast furnaces for the metal-making industry. Additionally, numerous new technologies are nearing commercial readiness but may remain limited to niche roles due to the relative performance versus investment costs.

**High readiness for low to medium temperature electrification:** Case studies

across industry show electrification technologies rapidly advancing in the low, low-medium and medium grade heat industries. The technology is particularly effective for applications utilising hot water, boiling or steam generation. Due to the cyclical (e.g. batch processing) nature of many industrial processes, thermal storage is an opportune pairing when electrifying many low-to-medium temperature grade industries.

### **Electrification of high-temperature remains complex and case-dependent:**

Metal, Cement and engineering industries are energy intensive, requiring complex heating processes. As such, application of high-grade electric technologies has limited viability due to dimensions, precision or grid capacity limitations. While high-grade heat remains challenging to electrify, some commercial technologies are now available, though their applicability and cost-effectiveness vary across industries.

**Heat storage is underutilised:** Despite offering clear economical, efficiency and emissions benefits to industries, heat storage has remained underutilised. It is rarely seen implemented alongside Power-to-Heat solutions, and is more commonly seen in combination with renewable heat generation (e.g. Concentrated Solar Plants). Dense crushed rock is gaining attention as a storage mechanism, as it offers a cheap and effective way of offsetting peak hour electricity demand rates.

### **Thermal energy storage (TES) enhances flexibility in batch and modular processes:**

In Chemicals, and Food and Drink industries, which often utilise batch processes, TES enables firms to shift energy use to off-peak periods, improving the system efficiency. It is most effective when implemented with batch or

modular process lines and deployed along Power-to-Heat solutions.

### **Ireland's industrial heat electrification is developing, but lags behind EU:**

**While** having expansive pharmaceutical and food industries ideal for electrification, industrial heat electrification is still less common in Ireland than in other EU countries. Germany, Belgium and The Netherlands lead in electrification and heat storage technologies. These countries exhibit stronger public-private coordination in documenting and disseminating knowledge on heat electrification.

### **Accelerating Deployment: Priority Actions**

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While important steps have been taken in Ireland to support the deployment of P2H and thermal storage solutions, further action is needed. Key enablers include reducing electricity cost barriers, improving grid access, strengthening technical support, and aligning incentives. Real progress will require coordinated efforts from industry, policymakers, and system operators.

#### **For Industrial Sites**

- Conduct high-level heat demand mapping to identify electrification potential by process and temperature.
- Assess feasibility of mature P2H technologies and thermal storage integration.
- Explore onsite renewables and flexibility options to improve economics and reduce grid dependency.
- Begin with low-risk pilots and build internal capacity through targeted staff training.

#### **For Policymakers and Regulators**

- Adjust tariffs and tax structures to close the electricity cost gap with fossil fuels.
- Expand and tailor financial supports, including incentives for early replacement of fossil systems.
- Establish a national alliance and decentralised technical support structures to bring together policymakers, industry, utilities, and the research community, creating a coordinated platform for strategy development, target-setting, and knowledge exchange.
- Design performance-based financial incentives, including scrappage schemes and capex rebates, that reward replacement of fossil-fuel heating systems with low-emission alternatives, and scale support according to environmental impact.

#### **For Grid and Market Operators**

- Adapt electricity market structures to better reward flexible demand, allowing industrial users with P2H and TES systems to participate in demand response and balancing services.
- Improve grid connection processes and timelines for industrial electrification projects, especially for large loads associated with electric heating technologies.
- Support local grid planning that considers future industrial electrification needs, ensuring capacity is available where demand is expected to grow.
- Collaborate with industry to forecast and integrate electrified heat demand, improving system planning and reducing uncertainty for large energy users.

Ireland can simultaneously reduce curtailment, decarbonise its hardest to abate heat loads, and strengthen energy security by scaling Power-to-Heat plus storage within a Circular Energy framework. The technology suite exists, policy levers are in place or emerging, and the business case improves as

renewable penetration and carbon pressures rise. The next phase is targeted, process level deployment, supported by coherent incentives and market signals that reward flexibility, storage, and onsite optimisation.

# Acronyms

<b>AC</b>	Alternate Electric Current	<b>MAS</b>	Microwave-Assisted Synthesis
<b>APIs</b>	Active Pharmaceutical Ingredients	<b>MtCO<sub>2</sub>eq</b>	Megatons Carbon Dioxide Equivalent
<b>CEG</b>	Clean Export Guarantee	<b>MVR</b>	Mechanical Vapour Compression
<b>CHP</b>	Combined Heat and Power	<b>MW</b>	Megawatt
<b>COP</b>	Coefficient of Performance	<b>NECP</b>	National Energy and Climate Plan
<b>CSP</b>	Concentrated Solar Power	<b>NSV</b>	Net Selling Value
<b>CST</b>	Concentrated Solar Thermal	<b>OSB</b>	Oriented Strand Boards
<b>DRI</b>	Direct Reduced Iron	<b>P2H</b>	Power to Heat
<b>DSO</b>	Distribution System Operator	<b>PCM</b>	Phase Change Materials
<b>EAf</b>	Electric Arc Furnace	<b>PV</b>	Photovoltaic
<b>EAS</b>	Energy Auditing Scheme	<b>RDAs</b>	Regional Development Agencies
<b>EEOS</b>	Energy Efficiency Obligation Scheme	<b>RDH</b>	RotoDynamic Heater
<b>eHeat</b>	Electric Heat	<b>RED III</b>	Renewable Energy Directive
<b>EHPA</b>	European Heat Pump Association	<b>RES</b>	Renewable Energy Source
<b>EnMS</b>	Energy Management System	<b>RF</b>	Radio Frequency
<b>ETS</b>	Emissions Trading Scheme	<b>RHO</b>	Renewable Heat Obligation
<b>EU</b>	European Union	<b>RNG</b>	Renewable Natural Gas
<b>FLIE</b>	Fieldlab Industrial Electrification	<b>RRF</b>	Recovery and Resilience Facility
<b>gCO<sub>2</sub>eq/kWh</b>	Grams Carbon Dioxide Equivalent per Kilowatt Hour	<b>SBTi</b>	Science Based Targets Initiative
<b>GHG</b>	Greenhouse Gas	<b>SDGs</b>	Sustainable Development Goals
<b>GVA</b>	Gross Value Added	<b>SEAI</b>	Sustainable Energy Authority Ireland
<b>GW</b>	Gigawatt	<b>SHS</b>	Sensible Heat Storage
<b>GWh</b>	Gigawatt hour	<b>SME</b>	Small-Medium Enterprise
<b>GWP</b>	Global Warming Potential	<b>SSRH</b>	Support Scheme for Renewable Heat
<b>HRSG</b>	Heat Recovery Steam Generation	<b>TCHS</b>	Thermochemical Heat Storage
<b>IEA</b>	International Energy Agency	<b>TES</b>	Thermal Energy Storage
<b>kW</b>	Kilowatts	<b>TRL</b>	Technological Readiness Level
<b>LHS</b>	Latent Heat Storage	<b>TWh</b>	Terawatt hour

# Section 1: An Overview of the Current status of Energy systems in Ireland

Ireland's transition to renewable electricity production systems is pivotal for achieving decarbonisation, enhancing energy security, and fostering economic growth. This section explores the crucial role of renewable electricity in Ireland, examines the lifecycle impacts of renewable energy systems, discusses curtailment issues, analyses heat demand with a focus on industrial heat, and delves into strategies for decarbonising industrial heat. Highlighting why energy revalorisation by converting what would be excess power, possibly curtailed, into heat is aligned with circularity goals.

The concept of energy revalorisation, which involves converting surplus or curtailed electricity into useful heat, aligns with Ireland's circular economy objectives. The National Energy Projections 2024 report by the Sustainable Energy Authority of Ireland (SEAI) emphasizes the need for systemic change, including reducing energy demand and disincentivizing wasteful energy use, to transition towards a sustainable, net-zero, circular economy. Additionally, the European Commission's Circular Economy Action Plan underscores the importance of resource efficiency and waste minimization, which are integral to circularity goals.

## 1.1 The Role of Renewable Electricity Production Systems in Ireland

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Renewable electricity is central to Ireland's strategy for reducing greenhouse gas emissions. Ireland's Climate Action Plan sets out ambitious goals, including generating 80% of electricity from renewable sources and cutting emissions from the electricity sector by 75% by 2030. To achieve this, the plan includes 9 GW of onshore wind, at least 5 GW of offshore wind, and 8 GW of solar photovoltaic (PV) capacity by 2030 (Climate Action Plan, 2024).

## 1.2 Ireland's Total Energy Capacity in 2023

In 2023, Ireland's wind energy sector achieved a record-breaking generation of 11.7 TWh, driven by an installed wind capacity of 4.74 GW (SEAI, 2024a). Although solar PV still represents a smaller share of generation, its role is steadily growing within the energy system. Approximately 505 MW of new solar PV capacity was deployed in 2024, nearly doubling the total installed

capacity from 680 MW in 2023 to around 1,185 MW by mid-2024, a growth that has been largely driven by utility-scale projects of 5 MW or more (ISEA, 2024). On top of that, as of 2023, the all-island grid was supported by circa 750 MW of operational batteries and 750 MW of industrial and commercial customers able to provide demand side flexibility (Renewable Energy Ireland, 2023).

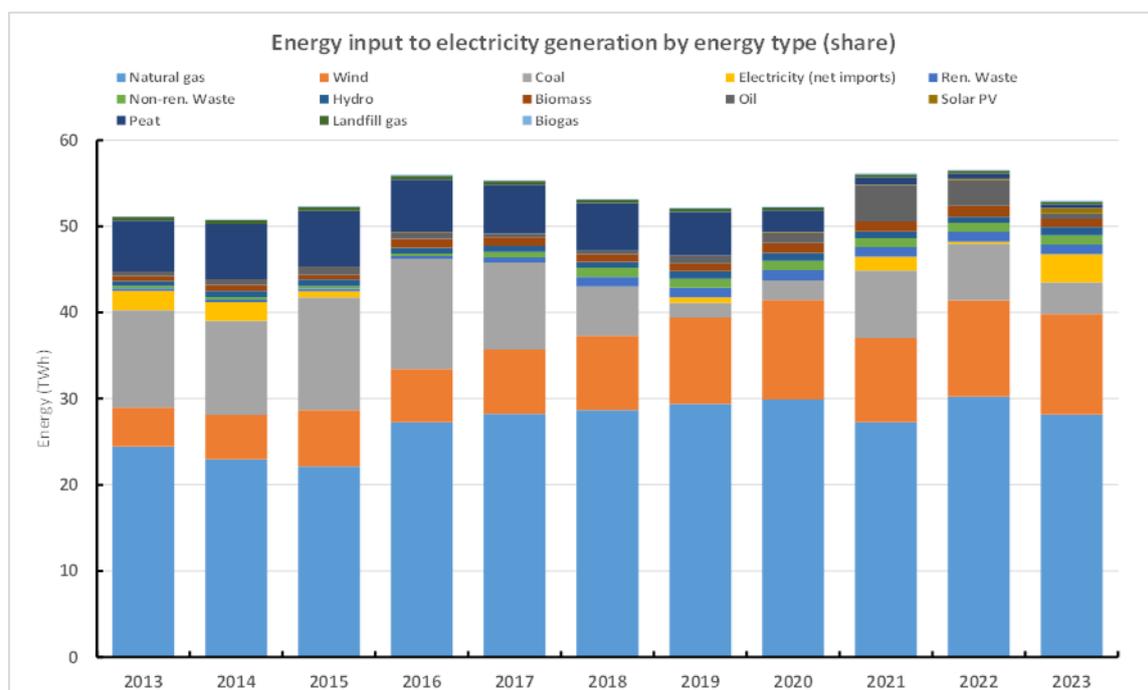


Figure 1: SEAI Energy input to electricity generation (2013-2023) (SEAI, 2024)

## 1.3 The decarbonisation potential of renewable energy systems

The decarbonisation potential of investing in renewable energy systems can be seen in **Figure 2** which illustrates the emissions avoided through renewable electricity generation in Ireland over recent years.

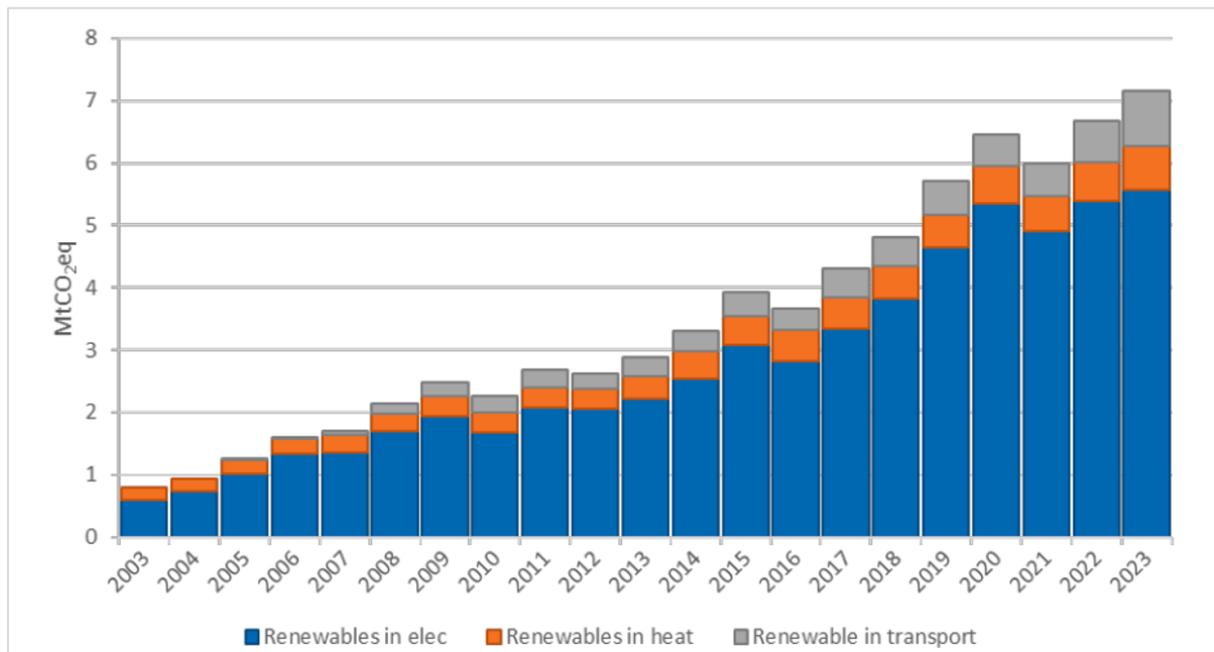


Figure 2: Avoided emissions from renewable energy in Ireland. (SEAI, 2024)

### 1.3.1 Renewable Electricity and Energy Security

Beyond environmental benefits, renewable electricity significantly enhances energy security, vital for both the nation and businesses investing in renewable energy sources. By reducing reliance on imported fossil fuels, Ireland can reduce exposure to volatile global energy markets, ensuring a more stable and predictable energy supply. This stability is crucial for businesses, as it mitigates the risks associated with energy price fluctuations and potential supply disruptions, thereby fostering a more favourable investment climate.

### 1.3.2 Renewable Electricity and Economic Growth

The renewable energy sector in Ireland has become a major driver of economic growth, attracting significant investment while supporting job creation and technological innovation. According to SEAI, achieving the country's energy transition goals could require up to €19 billion in capital expenditure annually by 2030, representing a transformative opportunity for the Irish economy. This level of investment not only stimulates economic activity but also positions Ireland as a frontrunner in renewable energy, fostering innovation and a resilient green jobs market (SEAI, 2025a)

For example, reaching the government's target of 8 GW of solar PV capacity by

2030 is projected to contribute over €2.3 billion in Gross Value Added (GVA) between 2025 and 2030, while supporting between 5,480 and 7,130 jobs across the country (SEAI, 2024b). Offshore wind development offers even greater potential: a value chain analysis by University College Cork estimates that delivering 2.5 – 4.5 GW of offshore wind capacity by 2030 could create between 11,424 and 20,563 supply chain jobs, contributing €763 million to €1.4 billion in GVA (Kandrot et al., 2020).

Beyond national figures, wind energy is also delivering tangible benefits at the local level. Wind farms contribute nearly €50 million each year to County Councils, supporting infrastructure such as roads, libraries, and public services—particularly in rural communities (Renewable Energy Ireland, 2023).

### 1.3.3 Lifecycle Impact of Renewable Energy Systems

In Ireland, the life cycle Global Warming Potential (GWP) of electricity from solar PV is estimated at around 70 gCO<sub>2</sub>-eq/kWh (Murphy and McDonnell, 2017) and for wind energy, approximately 15 gCO<sub>2</sub>-eq/kWh<sup>1</sup> - while the operational phase of renewable energy sources (RES) is virtually emission-free, the manufacturing, transportation, installation, and end-of-life stages involve material extraction, energy use, and waste generation that result in lifecycle emissions. It should be noted that this impact is significantly lower in comparison to electricity generation from natural gas (650 gCO<sub>2</sub>-eq/kWh) or oil (970 gCO<sub>2</sub>-eq/kWh)<sup>2</sup>.

A **carbon dioxide equivalent** or **CO<sub>2</sub> equivalent**, abbreviated as **CO<sub>2</sub>-eq** is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential.

**Global-warming potential**, abbreviated as **GWP**, is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere.

The global-warming potentials (GWPs) currently used are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1.

Source: [Statistics Explained - Eurostat](#)

<sup>1</sup>ecoinvent data v3.9 accessed via openLCA (GreenDelta GmbH, 2023)

<sup>2</sup>ecoinvent data v3.9 accessed via openLCA (GreenDelta GmbH, 2023)

## The Life Cycle Global Warming Potential (GWP) of Electricity Generation

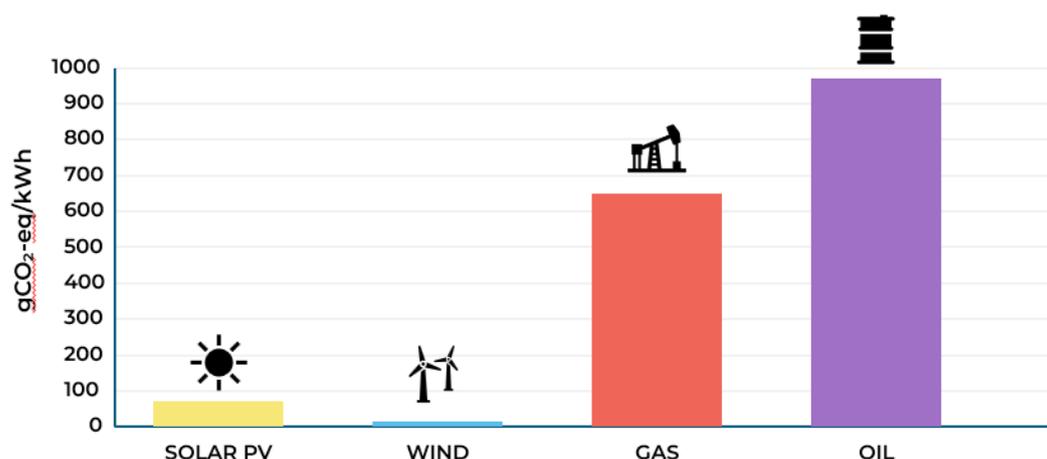


Figure 3: The Life Cycle Global Warming Potential (GWP) of Electricity Generation

While there is no doubt that the benefits of RES like solar photovoltaics (PV) and wind energy far outweigh their impacts - especially when compared to conventional fossil-based electricity generation - it is still essential to acknowledge and address the environmental footprint of these technologies across their full life cycle.

### 1.3.4 Renewable Energy Sources & Critical Raw Materials

Producing these technologies requires critical raw materials - such as silver, silicon, indium, and copper for PV panels, and rare earth elements like

neodymium and dysprosium for wind turbine magnets. The mining and processing of these materials can lead to environmental degradation, supply chain vulnerabilities, and social impacts in producing countries. Additionally, growing volumes of end-of-life equipment pose challenges. Without effective recycling and circularity strategies, PV panels and wind turbine blades risk ending up in landfills, contributing to environmental waste. To mitigate these impacts and enhance the overall sustainability of renewable energy systems, continuous improvements in technology, recycling processes, and circular economy practices are essential.

	Solar	Wind	Battery storage	Hydrogen	Electricity networks
Copper	●	●	●	●	●
Cobalt	●	●	●	●	●
Nickel	●	●	●	●	●
Lithium	●	●	●	●	●
Rare Earth Elements	●	●	●	●	●
Chromium	●	●	●	●	●
Zinc	●	●	●	●	●
Platinum Group Metals	●	●	●	●	●
Aluminium	●	●	●	●	●

Colour indicates the relative importance of minerals for a particular clean energy technology ( ● = high; ● = moderate; ● = low).

Figure 4: Critical Mineral Needs For Clean Energy Technologies (Green Purposes, 2023)

Most importantly, given the finite nature of critical raw materials and the environmental costs associated with their extraction and disposal, it's imperative to optimize the deployment and utilization of RES. Ensuring that renewable energy systems operate at their highest efficiency and capacity not only maximizes their environmental benefits but also justifies the resources invested in their production and infrastructure.

### 1.3.5 Curtailment and Constraint of Renewable Energy

Integrating renewable energy sources like wind and solar into Ireland's power system presents challenges, particularly concerning the efficient utilization of generated electricity. Two primary issues are curtailment and the management of surplus energy from small-scale producers.

Dispatch-down<sup>3</sup> refers to the reduction of renewable energy output when generators are instructed to limit their production, either due to local network constraints (constraint) or system-wide operational requirements (curtailment). Constraint refers to limitations in a local distribution network in handling high levels of intermittent generated electricity (from wind and solar), usually solved by the shutoff or throttling of a subset of turbines in order to alleviate the stress on the network. Curtailment refers to the limitation of system-wide networks, where the relative end-use demand is low compared to the supply available, often resulting in the reduction of any or all intermittent generation in order to alleviate the problem.

In 2023, Ireland and Northern Ireland experienced a dispatch-down of approximately 1,663 GWh of wind energy, representing 10.7% of the total available wind energy. Additionally, solar energy faced a dispatch-down of 50 GWh, accounting for 9.1% of the total available solar energy (Eirgrid, 2023).

This highlights the value of optimising the use of energy at the point of generation, particularly in scenarios where grid constraints would otherwise prevent its export. By aligning local demand with renewable generation, it is possible to reduce energy waste and make better use of clean electricity that would otherwise be curtailed or dispatched down.

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<sup>3</sup> "Dispatch down is the broader term used in the Irish power system to describe any time a generator is instructed not to generate electricity even though it technically could. It includes both curtailment (for system-wide security) and Constraint (for local grid limitations).

### **1.3.6 Surplus Energy from Small-Scale Producers**

Small-scale renewable energy producers, such as businesses and community groups, often generate electricity primarily for self-consumption. However, mismatches between production and demand are common resulting in surplus energy. According with an ESB report, from February 2022 to August 2023, over 81 GWh of electricity exports to the grid were recorded (Networks, 2023).

Since July 2022, Irish homeowners and businesses have been eligible to sell their surplus solar electricity back to the grid under the Clean Export Guarantee (CEG) tariff. However, while the CEG creates a right to be paid for exported electricity, it doesn't guarantee the producer will be able to export all the excess energy, particularly in areas with grid saturation or periods of low grid demand. Additionally, the export price is typically lower than the import price.

Thus, optimising onsite consumption is recommended, typically offering better value, but also because exporting surplus electricity to the grid may not always be possible.

### **1.3.7 Addressing the Challenges**

Addressing curtailment and effectively managing surplus energy from independent producers is crucial for maximising the benefits of renewable energy investments in Ireland. Optimising the use of energy onsite is often the most effective approach, as it

reduces dependence on grid export and ensures better use of generated power.

Several strategies can be considered. Demand-side management, for example, encourages industries to shift their energy consumption to align with periods of high renewable generation. Battery storage systems can also play a role by storing excess electricity and releasing it when needed, though their cost, scalability, and environmental

footprint must be carefully considered. Alternatively, converting surplus electricity into heat - an energy form that is often easier and more cost-effective to store - can offer a practical and sustainable solution, particularly when integrated into local thermal uses. Exploring these and other innovative approaches can enhance energy efficiency and contribute to a more sustainable and resilient energy system.

## 1.4 Heat Demand in Ireland and Decarbonisation of Industrial Heat

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In Ireland, heat-related activities are a significant contributor to both energy consumption and greenhouse gas emissions, accounting for 38% of energy-related CO<sub>2</sub> emissions in 2023 — equivalent to 12.0 MtCO<sub>2</sub>eq — and representing a major share of final energy consumption across all sectors. In recent years, efforts to improve energy efficiency and reduce emissions in the heat sector have begun to show results. In 2023, Ireland's overall heat demand decreased by 2.64 TWh, with reductions observed across all economic sectors. This contributed to the lowest recorded heat-related emissions to date. However, despite this progress, over 90%

of heat demand is still met with fossil fuels, indicating that a significant transformation is still required.

In 2023, manufacturing combustion processes alone contributed approximately 10% of Ireland's total greenhouse gas emissions, making it the largest source of emissions within the industrial sector. As illustrated in **Figure 5** emissions from manufacturing combustion consistently account for around two-thirds of total industry emissions, highlighting the sector's strong dependence on fossil-fuel-based thermal energy.

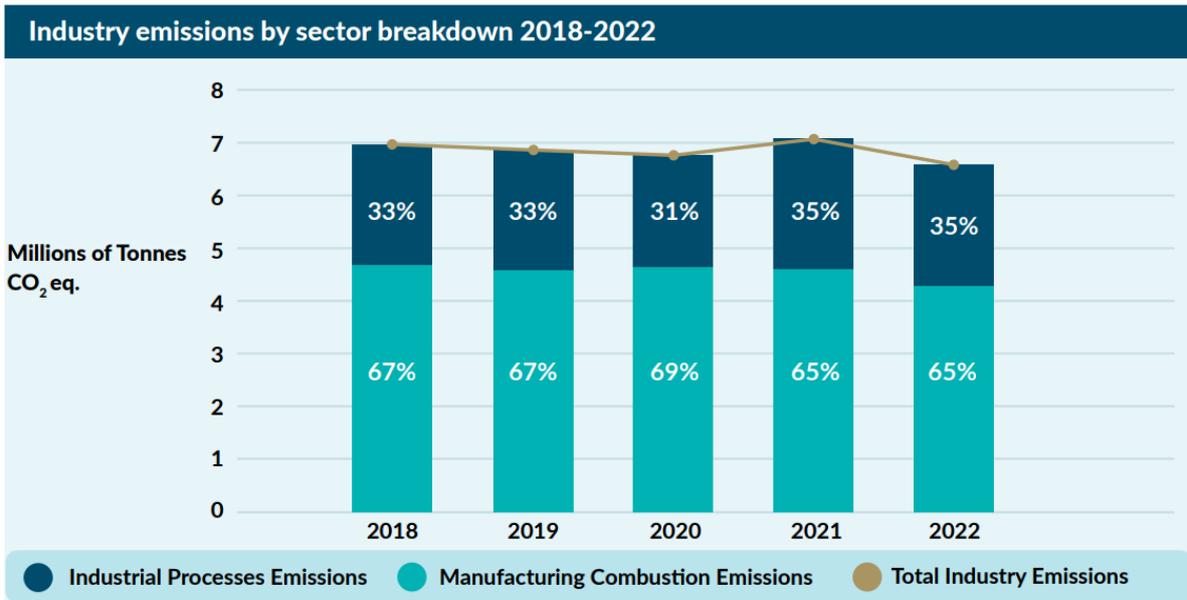


Figure 5: Industry emissions by sector breakdown 2018-2022. (DETE, 2024)

This reliance is closely tied to the demand for high- and medium-grade heat, particularly in energy-intensive sectors. As shown in **Figure 6**, more than half of industrial heat demand falls into these higher temperature categories, with just a few sectors – metals and cement, in particular – accounting for the bulk of it. This distribution

underscores the complexity of the decarbonisation challenge: each sector has different process requirements and therefore will require specific approaches and technological solutions depending on the temperature grade and energy intensity of their heat demand.

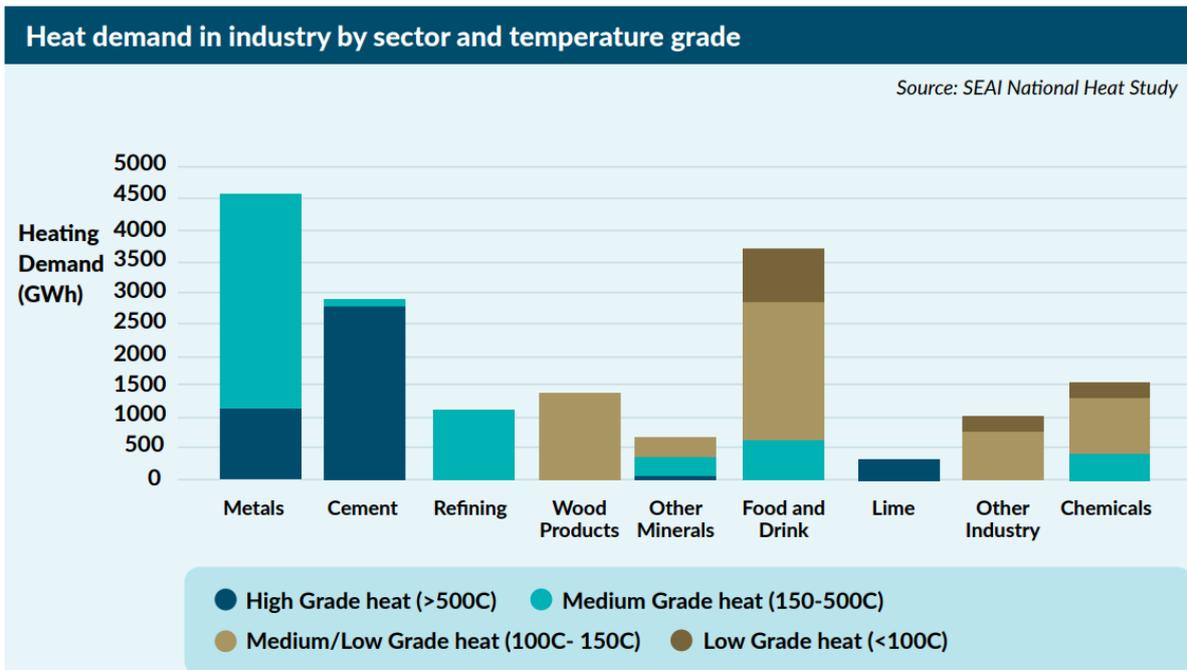


Figure 6: Heat demand in industry by sector and temperature grade. (National Heat Study-SEAI, 2022)

Decarbonising industrial heat is critical for Ireland to meet its climate objectives. The "Roadmap for the Decarbonisation of Industrial Heat" outlines strategies such as electrification of heat processes, adoption of renewable energy sources, and implementation of energy efficiency measures. Electrification, in particular, is poised to play a significant role. The deployment of technologies like

electrode boilers, which convert excess renewable electricity into usable heat, can reduce carbon emissions and enhance energy efficiency. However, this transition will place significant demand on the energy system, necessitating a transformative rollout of renewable generation and reinforcement of the electricity grid (DETE, 2024)

## 1.5 Summary

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Ireland's progress in expanding renewable electricity generation represents a vital opportunity to address not only carbon emissions, but also systemic inefficiencies across the wider energy system. However, as outlined throughout this section, challenges such as curtailment, grid constraints, and the underutilisation of surplus electricity, especially from small-scale and industrial producers, continue to limit the full potential of renewable energy sources.

Power-to-heat technologies, particularly when combined with thermal storage, offer a strategic pathway to revalorise surplus electricity and maximise the value of installed renewable capacity. These solutions are well aligned with national circular economy principles, as they promote resource efficiency,

minimise waste, and enhance energy resilience by encouraging local, flexible, and low-carbon energy use. By converting excess electricity into usable heat for industrial and commercial processes, Ireland can reduce fossil fuel dependence in one of its most emissions-intensive sectors while addressing curtailment and grid limitations.

This report will explore the role of power-to-heat solutions, alongside heat storage systems, as enablers of a more circular, low-carbon, and efficient energy model for Irish industry. The technologies examined offer not just a way to decarbonise heat, but also to stabilise the electricity system, reduce system losses, and create additional value from Ireland's growing renewable electricity assets.

# Section 2: Drivers and Technologies

## 2.1 The Unique Characteristics of Heat

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Heat, or thermal energy, plays a unique role in the energy system, particularly in industry, where it represents a major end-use demand.

Heat has the advantage of being a highly flexible form of energy that opens valuable opportunities for efficiency and decarbonisation. On the one hand, heat can be obtained from a variety of sources, including (surplus) electricity, industrial waste heat, solar thermal, or biomass, allowing industries to reduce reliance on fossil fuels and lower their primary energy consumption. On the other hand, unlike electricity, thermal energy can be stored relatively easily and cost-effectively using established technologies such as water tanks or molten salts.

These characteristics make it possible to decouple energy production from use, enabling load shifting and improved integration of variable renewable electricity. Thermal storage systems can absorb excess electricity when supply exceeds demand, helping to avoid grid curtailment while reducing the need for additional energy input to meet heat demand at other times.

**“Thermal energy storage provides the essential flexibility to integrate high shares of solar and wind power.”**

**(Renewable Energy Agency, 2020)**

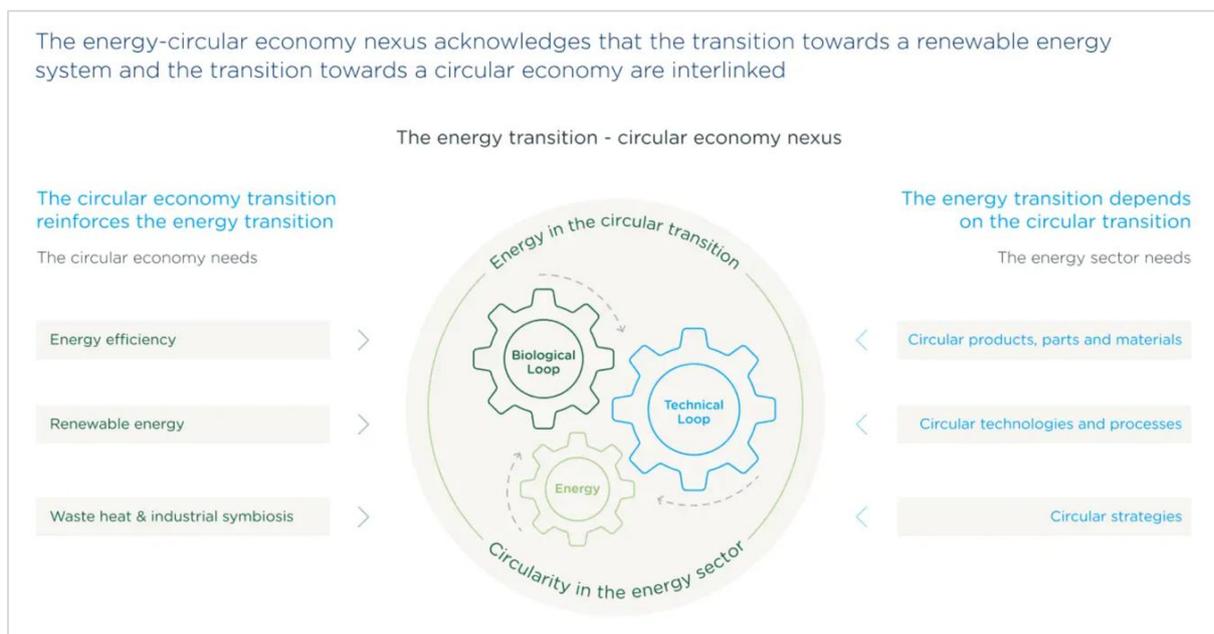
In many industrial processes, decarbonising heat supply is key to reducing overall emissions. By converting power to heat when electricity is clean and available, and storing that heat for later use, companies can reduce fuel use, lower emissions, and optimise their energy systems ('Power-2-Heat', no date)

## 2.2 Energy Transition and Circular Economy

The term “Circular Energy,” as used throughout this document, refers to energy transition strategies that reflect circularity principles, such as recovering, reusing, and reintegrating energy that would otherwise be wasted - in this case specifically applied to industrial heat decarbonisation.

While these practices (e.g. power-to-heat, thermal storage, industrial waste heat recovery) are not new, nor exclusive

to the circular economy framework, they represent a clear nexus between circular thinking and energy systems transformation, as illustrated in **Figure 7**. The intention is not to rebrand established energy transition concepts, but to highlight where circular principles and energy transition approaches reinforce one another, especially in efforts to reduce emissions, minimise primary energy demand, and increase system efficiency and flexibility.



**Figure 7:** The interdependence of circular economy and energy transition (Ramboll Group, 2023)

By converting surplus or low-cost renewable electricity into heat, power-to-heat systems allow industrial sites to reduce reliance on fossil fuels for process heating, lowering both energy costs and carbon emissions. When combined with thermal storage, this heat can be stored and used when needed, improving flexibility and resilience in operations. These systems can also help stabilise the electricity grid if they are set to absorb

excess renewable generation during peak supply periods. For industries with variable heat demand or access to low-cost electricity as on-site solar or wind, power-to-heat with storage enables better energy management, supports decarbonisation goals, and can unlock new business models such as participation in demand response or energy communities.

The following approaches summarise key energy transition pathways in the heating sector that align with the principles of circular thinking:

1. **Electrification:** Replace fossil heat with electric systems, supporting the integration of variable renewable energy.
2. **Efficiency:** Adoption of more efficient electric technologies, reducing the amount of primary energy required.
3. **Flexibility:** Shift electric heat generation to match renewable energy availability, leveraging storage systems.

According to the European Commission’s Strategy for Energy

System Integration, such approaches are essential to increase overall energy efficiency and decarbonise hard-to-electrify sectors by linking electricity, heating, cooling, and industry (Europarl, 2025). The International Energy Agency (IEA) also emphasises in its Net Zero by 2050 report that integrating surplus renewable electricity through sector coupling, including power-to-heat conversion, can significantly reduce curtailment and optimise system-level energy use. Similarly, IRENA highlights that thermal storage plays a critical role in enabling this circular use of energy, especially when used to capture otherwise unused heat or off-peak electricity for later productive use. These strategies reflect circular economy principles by minimising waste while extending the value of energy inputs.

## 2.3 Policy Drivers and Government Support for Circular Energy

Ireland has introduced a range of national policies, support schemes, and regulatory measures aimed at facilitating the transition to cleaner energy and reducing greenhouse gas

emissions, in line with EU and international commitments. The key policy and schemes at national level are represented in **Table 1**.

**Table 1:** Policy and frameworks to drive/support industries toward Circular Energy at a national level

Regulation / Initiative	Aim	Possible Enabler or Barriers/Constraints for Circular Energy Solution
<b>National Energy and Climate Plan (NECP) 2021–2030</b>	Outlines Ireland’s plan to meet EU climate targets by cutting emissions, boosting renewables, improving energy efficiency, and ensuring energy security. It sets policies and measures for 2030 and supports progress toward climate neutrality by 2050.	Saving obligations in accordance with the requirements of Article 5 and Article 7 of the Energy Efficiency Directive (EU/2023/1791)

Regulation / Initiative	Aim	Possible Enabler or Barriers/Constraints for Circular Energy Solution
<b>Energy efficiency obligation scheme (EEOS)</b> (SEAI, no date a)	Increasing energy savings (as a result of an energy efficiency improvement).	Some examples of the types of technologies which can be supported under EEOS are Electrification of Heat, Servicing, set point regulation etc.
<b>S.I. No. 426/2014 – European Union (Energy Efficiency Regulations)</b>	Transposes the EU's 2012 Energy Efficiency Directive (2012/27/EU) into Irish law. Enforced through the Energy Auditing Scheme (EAS) managed by SEAI, with compliance requirements for designated entities.	Applicable only to large enterprises (employing ≥250 people or with significant turnover and balance sheet totals) to conduct energy audits every four years. Information used for compliance can be used for deployment of an Energy Management System. ISO50001 certification automatically demonstrates compliance for a period of four years.
<b>Support Scheme for Renewable Heat (SSRH)</b> (SEAI, no date b)	The Support Scheme for Renewable Heat provides financial support to non-domestic heat users not covered by the EU ETS, encouraging the switch to renewable heating technologies and helping reduce emissions.	There are two types of financial supports available under this Support Scheme: <ul style="list-style-type: none"> <li data-bbox="963 1211 1362 1357">• An installation grant of up to 40% for investment in renewable heating systems, and</li> <li data-bbox="963 1379 1362 1491">• Support for the operation of the renewable heating system for up to 15 years.</li> </ul>
<b>Renewable Heat Obligation (RHO)</b> (Renewable Heat Obligation, 2025)	Places a legal requirement on fossil fuel suppliers in the heat sector to incorporate renewable heat, driving demand for low-carbon heating and supporting national decarbonisation targets.	By mandating suppliers to include a share of renewable heat, creates market demand, incentivises investment, and accelerates the switch from fossil-based to renewable heating technologies.

The EU is driving the energy transition through a broad set of policies that serve as the foundation for national strategies, obligations, and support schemes across Member States. **Table 2** represents the key policy and schemes.

**Table 2:** Policy and frameworks to drive/ support industries toward Circular Energy at EU level

<b>Regulation / Directive</b>	<b>Aim</b>	<b>Possible Enabler or Barrier/Constraint for Circular Energy Solution</b>
<b>Renewable Energy Directive (RED III) – (EU) 2023/2413</b> (EU Chemicals Platform, 2025)	Entered into force on 20th November 2023 aiming for a 42.5% renewable energy share by 2030 (binding at EU level), with efforts to reach 45%.	Streamlined processes for renewable energy projects, reducing bureaucratic barriers and accelerating deployment and encouraging research and innovation in advanced biofuels and emerging renewable technologies.
<b>Energy Efficiency Directive – (EU) 2023/1791 (Recast Energy Efficiency Directive)</b> (European Commission, 2023), (ee-ip, 2024)	Consisting of 9 guidance documents to help EU countries when transposing its different elements into national law ensuring energy efficiency considerations are integrated into all relevant policy and investment decisions.	Increased the energy savings obligation. Member States are to bring into force the laws, regulations and administrative provisions transposing Articles 8, 9, 10 by 11 October 2025.
<b>REPowerEU Plan</b> (The European Green Deal, 2024)	Designed to reduce the EU’s dependence on fossil fuel imports from Russia.	The Commission has allocated nearly €300 billion to implement the Plan, with the Recovery and Resilience Facility (RRF) playing a central role by supporting investments in energy infrastructure, cross-border connections, and efficiency improvements.

### 2.3.1 Other Drivers for the application of Circular Energy

In the lack of binding national legislation specifically facilitating Circular Energy strategies for industry in Ireland, the primary drivers for implementation are industry-led (Department of Climate, Energy and the Environment, 2021) (Enterprise Ireland, no date). Irish industrial stakeholders, particularly in

sectors such as manufacturing, food processing, and pharmaceuticals, are advancing Circular Energy adoption through internal sustainability goals, cost reduction strategies, and carbon neutrality targets. This is further influenced by corporate compliance with international climate and ESG standards (Europarl, 2022), reputational risk management, and increasing pressure from global supply chains to

decarbonize operations (EY - Ireland, 2021).

Although specific regulatory frameworks are still evolving, several voluntary standards, industrial guidance

documents, and international frameworks act as credible references to guide and support Circular Energy initiatives in the industrial context, as presented in **Table 3**.

**Table 3:** Other frameworks toward Circular Energy

Framework / Guideline	Aim and benefits
<b>ISO50001: Energy Management Systems</b>	Provides a framework for organizations to improve energy efficiency through policy development, data-driven decisions, and performance measurement. It promotes continual improvement in energy management.
<b>ISO14001: Environmental Management Systems</b>	Offers a structured approach for organisations to develop and maintain an EMS, supporting continuous improvement in environmental performance and helping reduce their overall environmental impact.
<b>Science Based Targets initiative (SBTi)</b> (SBTi, no date)	Helps companies and financial institutions set science-based emissions reduction targets. It provides standards, tools, and guidance to enable organizations to align their greenhouse gas (GHG) reduction targets with the goals of the Paris Agreement, aiming to limit global warming.
<b>The Sustainable Development Goals (SDGs)</b> (SDGs, 2025)	Goal 7 of the Sustainable Development Goals, 'Affordable and Clean Energy,' serves as a key policy driver for Circular Energy strategies. It is aimed at increasing the share of renewable energy in the global energy mix and calls for doubling the global rate of improvement in energy efficiency (SEforAll, 2025)

These instruments encourage industries to make proactive investments in energy innovation, reduce operational risk, and future-proof their competitiveness in a decarbonizing economy. Collectively, they contribute to

advancing an industrial energy transition aligned with circularity principles including both national and EU climate objectives.

## 2.4 Power-to-Heat Technologies to Support a Circular Energy

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P2H technologies are pivotal in advancing a Circular Energy economy by converting surplus renewable electricity into usable thermal energy. This conversion facilitates the decarbonization of heating processes across residential, commercial, and industrial sectors (IEA, 2022). Technologies such as electric resistance heaters, heat pumps, induction heating, infrared heating and microwave heating enable the electrification of various heating applications (Fraunhofer ISE, no date). These methods offer precise control, high efficiency, and the potential for integration with renewable energy sources, thereby reducing reliance on fossil fuels (Agora-industry, 2024).

Integrating P2H systems with smart grids enhances the flexibility and stability of the energy system (Khalid, 2024). Smart grids can dynamically balance electricity supply and demand, accommodating the variability of renewable energy generation. Moreover, P2H technologies contribute to energy sector coupling by linking the electricity and heating sectors (Zhang et al., 2024). This integration allows for more efficient energy use and supports the utilization of low-grade waste heat, further promoting resource efficiency.

### **By facilitating the storage and reuse of energy, P2H systems support the principles of a circular economy, minimizing waste and optimizing resource utilization**

(Zhang, Liu and Sun, 2025).

The list below corresponds to electric heating technologies categorised based on the physical mechanism by which thermal energy is produced and delivered to a target material.

While **all the technologies listed contribute to electrification** by replacing fossil-fuel-based heating with electric alternatives, some offer significant advantages in **efficiency** and **flexibility**.

Technologies such as heat pumps, induction and microwave deliver strong **efficiency** gains by using less primary energy.

Resistive, induction, microwave, and heat pumps, can enhance **flexibility** when paired with thermal storage or smart control systems, enabling better alignment with renewable electricity availability.

Heat pump and induction heating offer advantages of both efficiency and flexibility.

## 2.4.1 RESISTANCE HEATING

 <b>WORKING PRINCIPLE</b>	 <b>NOTE:</b>
<p><b>Resistance heating works by converting electricity to heat using resistive elements, through Joule heating effect.</b></p> <p>This technology can provide heat to the target material in the following ways:</p> <ul style="list-style-type: none"><li>• <b>Indirect resistance heating:</b> the resistive element (e.g. heating coil in a water heater) generates and transfers heat to an intermediary fluid such as air, water, or oil, which then transfers the heat to the target material or space.</li><li>• <b>Direct heating, with a separate resistive element:</b> The resistive element transfers heat to the target materials, through physical contact or close proximity, without an intermediary fluid.</li><li>• <b>Direct resistance heating, or Ohmic heating, where the target material is the resistor:</b> The electric current is passed directly through the material to be heated and the material itself, due to its inherent electrical resistance generates heat.</li></ul> <p>When electricity is used to heat a fluid directly, or when it flows through the material itself as in ohmic heating, the conversion efficiency from electrical energy to thermal energy can reach 99-100%. However, the actual efficiency experienced at the point of use will depend on heat losses in the specific system or application.</p> <p><b>Note:</b> Electric boilers are a specific type of technology that falls within the category of resistance heating. These are widely used in industry for low-to-medium temperature process heat, offering a clean and easily controllable alternative to fossil-fuel boilers.</p>	<p><b>Joule Heating Effect (or Ohmic Heating):</b> When an electric current passes through a material, heat is generated and dissipated. This occurs because the current encounters a certain electrical resistance (the opposite of electrical conductivity) as it flows through the material.</p> <p>The amount of heat produced is proportional to the square of the current and the resistance of the conductor (also known as the resistive element).</p>

 <b>HEAT GRADE</b>
<p>Low, medium and high grade, with operating temperatures up to 1850°C (Agora-industry, 2024). Higher temperatures (up to 3000°C) can be reached but bring added technical complexity and costs (Thermcraft, Inc, 2016).</p> <p>Electric boilers in particular can typically reach temperatures up to 300 °C, with specialised designs capable of delivering heat up to 500 °C for high-temperature industrial processes.</p>

## RESISTANCE HEATING (CONT.)



### APPLICATIONS

Best suited for intermittent/batch operations. A (non-exhaustive list) of application examples can be seen as follows:

#### Food and Drink Industry

- Baking and cooking
- Pasteurisation
- Drying and dehydration
- Cleaning

#### Chemical Industry

- Heating of reactors and vessels
- Distillation
- Drying of powders and granules
- Sterilisation processes

#### Metal Industry

- Heat treatment (annealing, tempering, preheating)
- Soldering and brazing

#### Other Industries

- Drying paper and inks and Heating rollers in paper /printing Industry
- Dyeing and finishing (heat-setting) and Drying fabrics in Textile and Leather Industry



### BENEFITS

- Well established technology
- High efficiency
- Suitable for a wide range of temperature requirements or heat loads
- Enables fast and precise temperature control, essential in temperature-sensitive industries



### CHALLENGES

- Electricity cost may be higher compared to gas or biomass unless mitigated by renewables.
- Challenging to adapt existing production facilities to incorporate this technology.
- Less optimal for very high, continuous heat loads due to high electricity demand.
- Heat density of resistance heating (80 kW/m<sup>2</sup>) is a limiting factor.

## 2.4.2 INDUCTION HEATING



### WORKING PRINCIPLE

Induction heating operates based on the principles of electromagnetism. It works by converting electrical energy into a rapidly changing magnetic field, which induces small electric currents, called eddy currents, within a conductive material. These currents generate heat inside the material through the Joule effect. Induction heating is used to directly heat only electrically conductive materials without physical contact.

This technology has the advantage of being able to reach very high temperatures. It can be used either to directly heat the conductive material or to use that material as a medium to transfer heat. Its efficiency can reach up to 90%, depending on the application.



### NOTE:

#### Electromagnetic principles:

An alternate electric current (AC) passing through a wire generates a rapidly changing magnetic field (this is Ampere's Law).

By its turn, a changing magnetic field near a conductor material induces a current in that material (this is Faraday's Law).

Being a bulk material (and not a wire or loop), the induced currents swirl in closed loops within it -- these are known as eddy currents.

As seen previously, electric currents going through a conductor generate heat through the Joule effect.



### HEAT GRADE

Low, medium and high grade, with operating temperatures up to 3000 °C (superheating, 2025).

## INDUCTION HEATING (CONT.)



### APPLICATIONS

Ideal for batch or cyclic processes (such as moulding processes), due to the rapid start-up. It is particularly a good fit for processes that require contamination-free heating, due to contactless heat transfer, such as in the food and drink or pharmaceutical sectors. However, due to the ability of reaching high temperatures very quickly, it has been mostly employed in the metals industry (EnergyInnovation, 2025).

On the other hand, induction heating is not suitable for large batches of materials nor for processes where uniform heat is required across a large volume of surface, since the type of heating this technology offers is localised, and the depth of heat penetration is limited (Lucia et al., 2014)

A (non-exhaustive list) of application examples can be seen as follows:

#### Food and Drink Industry

- Sterilization of sealed metallic containers

#### Chemical Industry

- Heating metal pipes or tubes for fluid processes
- Preheating metal reactors or components

#### Metal Industry

- Heat treatment (e.g., hardening, annealing, tempering)
- Forging and metal melting (Vilchez et al., 2023)

#### Other Industries

- Brazing, welding, or bonding of metal parts and surface hardening of shafts, gears, etc in Automotive Industry (Meng, Cheng and Chan, 2011)
- Precision heat treatment of components (e.g., turbine blades, fasteners) in Aerospace Industry (Choi et al., 2015)



### BENEFITS

- Provides fast, localized, and controllable heat
- Provides high-temperature heat (Baliga, 2023)
- Minimal energy loss when heat is directly applied to the part
- Can operate at high capacities (up to 42 MW)



### CHALLENGES

- Only works on electrically conductive materials (metals, primarily)
- Only works on specific geometries
- Less suited for large-scale uniform heating

## 2.4.3 INFRARED HEATING



### WORKING PRINCIPLE

Infrared heating works by using a heat source (as a lamp or ceramic element) to emit infrared radiation, a type of electromagnetic energy. When this radiation hits the surface of a material, it is absorbed and converted into heat, warming the material from the outside in. It does not rely on direct contact or a fluid to transfer heat, making it fast and efficient for surface or thin-layer heating.

Infrared heaters can provide a power density between less than 10W/cm<sup>2</sup> of target surface to 100W/cm<sup>2</sup>.

The heat production efficiency can range from 56% to 96%, depending on the emitter material. On the other hand, heat transfer efficiency of infrared technologies depends deeply on the optical properties of the material being heated, in particular, their absorptivity, reflectivity and emissivity. Typically, infrared technology shows a very low heat transfer efficiency when applied to metals, but this efficiency can rise up to 90-96% if the materials being heated are, for example, wood or plastics.



### HEAT GRADE

Infrared heating can be used for applications that require low, medium and high grades of heat (Aboud et al., 2019). The temperature of the target material depends on their own optical properties.

The total power output provided by infrared heating depends on the wavelength of the emitted infrared, which in its turn depends on the temperature of the emitter. The image below shows the temperature different infrared heaters reach and the corresponding wavelengths of the radiation they emit.

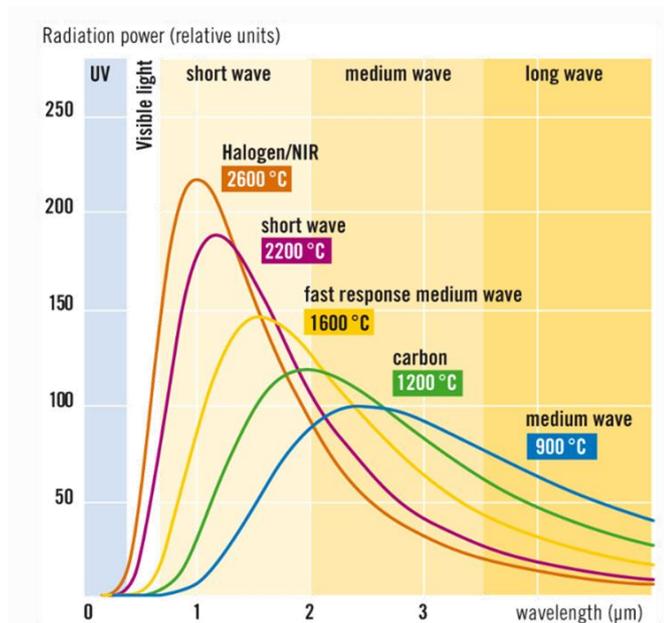


Figure 8: Infrared heater wavelengths and operating temperatures are shown as part of an overview of the standard types of heaters and their operating temperatures (Burkholder, no date)

## INFRARED HEATING (CONT.)



### APPLICATIONS

Infrared is best suited for surface heating, drying, and low-to-medium heat processes, especially where quick, clean, and controllable heat is needed (Khan, 2025).

#### Food and Drink Industry

- Surface cooking and baking (e.g. toasting, browning)
- Drying fruits, vegetables, and grains
- Sterilisation of packaging

#### Metal Industry

- Heat treatment (annealing, tempering, preheating)
- Soldering and brazing

#### Chemical Industry

- Heating of reactors and vessels
- Distillation
- Drying of powders and granules
- Sterilisation processes

#### Other Industries

- Ink drying and Paper coating and curing in paper /printing Industry
- Drying dyed or printed fabrics and Heat-setting synthetic fibers in Textile and Leather Industry
- Paint curing and Composite resin curing (e.g., carbon fiber) Automotive and composite Industry
- Plastic forming and softening, Heat shrinking, Solder pastes drying (some low-temp processes) in Electronics and Plastic Industry
- Sealing and sterilising plastic films and Shrink wrapping in Packaging Industry



### BENEFITS

- Efficient for surface heating; reduces process energy demand and enables clean electrified heat, very fast response time
- Modular and easy to install in conveyor or batch systems
- Rapid surface heating with no contact
- Homogeneity of heating with a high transfer rate
- Easy to control, integrate into automated lines  
(NGK INSULATORS, no date)



### CHALLENGES

- Limited penetration depth, since IR only heats the surface, not bulk material
- Sensitive to object geometry, so uneven surfaces may heat non-uniformly
- Needs clear line of sight – blocked or shaded areas receive less heat
- Efficiency depends on material – reflective or light-coloured surfaces may absorb less heat (30 – 75%)

## 2.4.4 DIELECTRIC HEATING - MICROWAVE AND RF

 <b>WORKING PRINCIPLE</b>	 <b>NOTE:</b>
<p><b>Microwave and Radio Frequency (RF) heating are forms of volumetric dielectric heating that use electromagnetic waves in the GHz and MHz frequency range, respectively, generated from electricity. These waves penetrate the material and cause molecular movement throughout its entire volume, resulting in uniform heating through internal friction.</b></p> <p>This working principle allows the technology to heat the whole volume of the material, rather than just its surface, operating through direct material heating.</p> <p>Microwave heating technology has a maximum efficiency of approximately 80%, while RF technology only reaches 60% (4AMTek, no date).</p>	<p>The electromagnetic waves are applied to a dielectric material (i.e. a material that with a very low electricity conductivity). The dipolar or polarisable molecules in the volume of material affected by the electromagnetic waves will keep constantly realigning with the changing field. And this constant movement causes internal (molecular) friction, heating the material uniformly throughout the whole volume.</p>

 <b>HEAT GRADE</b>
<p>Dielectric heating is mostly used for low and medium grade heating. Due to the nature of these technologies, the temperatures they can deliver depend on the properties of the materials being heated.</p> <p>RF heating is typically applied to plastics, textiles and food, generally reaches temperatures up to around 150°C.</p> <p>Microwave heating, when applied to food and other moist materials can raise temperatures to a few hundreds of degrees Celsius. However, microwave systems designed for high temperature processing can achieve between 1000 and 1800°C in absorptive ceramics or carbides.</p>



### APPLICATIONS - MICROWAVE HEATING

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Microwave heating is particularly suitable for batch or small-batch applications and modular setups. It is most useful for moist or dielectric materials, and in precision drying, heating, or chemical processes (Manufacturing, 2012). The selective, controlled, and efficient nature of microwave heating makes it ideal for niche applications, such as when precise, low-temperature, rapid, and volumetric heating is required without damaging sensitive materials.

#### Food and Drink Industry

- Cooking and tempering (e.g. frozen meat, chocolate)
- Drying and dehydration of moist foods
- Pasteurisation/sterilisation (microwave-assisted thermal processing)

(Ferrite Microwave Technologies, no date)

#### Chemical Industry

- Drying active pharmaceutical ingredients (APIs)
  - Microwave-assisted synthesis (MAS)
  - Sterilisation of sensitive products
- (McLoughlin, McMinn and Magee, 2003; Loh et al., 2008; Gawande et al., 2014)

#### Other Industries

- Drying herbs, grains, and biomass and Inactivation of pests or pathogens in agriculture and biomass industry
- Curing of cementitious materials and drying of ceramics, bricks, tiles in Construction materials and Ceramic industry
- Drying and sterilisation of medical waste in waste management

(Zimmermann, 2017)

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## DIELECTRIC HEATING - MICROWAVE AND RF (CONT.)



### APPLICATIONS - RF HEATING

Like microwave heating, RF heating is particularly suitable for batch or small-batch applications and modular setups. It is most useful for moist or dielectric materials, and in precision drying, heating, or chemical processes (Manufacturing, 2012), areas where conventional methods may fall short in terms of efficiency or product quality.

#### Food and Drink Industry

- Drying bakery goods, meats, and fruits
- Pasteurisation and microbial decontamination
- Defrosting and disinfestation of grains/nuts

(Wang et al., 2022), (Mahmood et al., 2022)

#### Chemical Industry

- Drying of granules during tablet production and Sterilisation of heat-sensitive compounds or materials in pharmaceutical industry
- Curing of Resin, polymers, Silicon
- Vulcanizing of Latex and Foam

(Stalam, no date)

#### Wood Product Industry

- Drying for hardwood lumber
- Disinfestation of wood and grain products (e.g. pest removal)

(Liu et al., 2019), (Mishra et al., 2025)

#### Other Mineral Industry

- Curing of Glass fibre
- Curing of Rock Fiber

(Rotkopf, no date)



### BENEFITS

- Enables efficient, targeted volumetric heating, lowering process energy needs
- Delivers uniform, deep volumetric heating throughout materials (not just surfaces)
- Rapid heating rate and faster penetration, reducing processing time (AIChE, 2021)



### CHALLENGES

- Sensitive to geometry and to heterogeneity of material composition: hot or cold spots can occur if the material composition is not uniform or if the load is too large
- Arcing risks: can't be used on metallic materials unless carefully engineered (Powder & Bulk Solids, 2023), (42 Technology, 2025)

## 2.4.5 ELECTRIC HEAT PUMPS

 <b>WORKING PRINCIPLE</b>	 <b>NOTE:</b>
<p><b>Electric heat pumps operate by converting electricity into heat through a refrigeration cycle powered by electrically driven compressors. Rather than generating heat directly, heat pumps transfer heat from one heat source (outdoor air, a body of water or the ground) to the end heat user, making them highly energy efficient, with coefficients of performance (COP) of between 3 and 6.</b></p> <p>Heat pumps use a refrigerant as the working fluid to absorb and release heat during the cycle. The heat medium can be either air or water, depending on the system design.</p> <p>Electric heat pumps offer modular and expandable capacity, allowing for flexible scaling based on demand. However, space requirements can vary significantly depending on the type of heat pump, heat output needs, and system configuration.</p>	<p>The refrigeration cycle is a process that transfers heat from one place to another using a specialised fluid: a refrigerant. Refrigerants are designed to easily change between liquid and gas at relatively low temperatures, which allows it to absorb and release heat very efficiently. In the cycle, the refrigerant first absorbs heat from the area to be heated or cooled. It is then compressed by an electrically powered compressor, which increases its temperature and pressure. The hot refrigerant then releases its heat to another medium, such as air or water, before it cools down and returns to its liquid state. This cycle repeats continuously and is the basis for how systems like refrigerators, air conditioners, and heat pumps work.</p>
 <b>HEAT GRADE</b>	
<p>Low- to medium-grade heat, with current systems capable of delivering temperatures up to 200 °C.</p>	

## ELECTRIC HEAT PUMPS (CONT.)



### APPLICATIONS

Heat pumps are particularly suitable for continuous processes, because they operate most efficiently under steady, long-duration loads. Since heat pumps heat fluids (water or air) their use is ideal for space heating, low to medium temperature industrial processes that require volumetric heating, or for the production of hot water or steam (EHPA, 2024):

#### Food and Drink Industry

- Producing steam for sterilisation, cleaning, or heating needs in addition to dehumidification and drying of food in food, beverage, and brewing sectors

#### Wood Product Industry

- Dehumidification and drying pulp/paper, textiles

#### Other Industries

- Dehumidification and drying of ceramics



### BENEFITS

- Extremely high efficiency, delivering several times more heat than electricity used, reducing primary energy
- High maturity, well established and proven technology



### CHALLENGES

- Available space can become a constraint when deploying heat pumps, especially for larger systems or where the design includes thermal storage or multiple units.
- Complex system integration, in some cases.
- Efficiency drops for higher temperatures

## 2.4.6 ELECTRIC ARC FURNACE (EAF)

 <b>WORKING PRINCIPLE</b>	 <b>NOTE:</b>
<p><b>Electric Arc Furnaces (EAFs) melt steel (or other metals) by generating intense electric arcs between graphite electrodes and the metal charge. These arcs form a high-energy plasma within the charge, causing very high temperatures in industrial furnaces. Various gases, as oxygen or argon, are added to support the melting process improve efficiency and control the chemical environment.</b></p> <p>EAFs rely on a complex mix of principles that intertwine plasma physics, Joule heating, thermodynamics, and electromagnetism to deliver highly efficient and powerful heat generation (Immgroupcn, 2020).</p>	<p>Electric arcs operate based on the physical principle of electric discharge through ionised gas, or plasma. When a high-current, low-voltage electrical flow jumps across a gap between electrodes, the surrounding gas becomes ionised and forms a plasma, allowing current to flow continuously. This process releases intense heat concentrated in a small area. The heating that occurs within an electric arc is primarily due to Joule heating, where electrical resistance in the arc and the metal generates high temperatures. In addition, strong electromagnetic fields around the arc can induce stirring in the molten metal, improving its homogeneity (CGEP, 2021).</p>
 <b>HEAT GRADE</b>	

High grade heat. The temperature within the arc column can exceed 6000°C, granting working temperatures of roughly 1600 – 1800°C in the furnace.

## ELECTRIC ARC FURNACE (EAF) (CONT.)

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### APPLICATIONS

- Electric Arc Furnaces (EAFs) are designed for bulk melting of metals at extremely high temperatures. They are well-suited for applications requiring flexible operation and variable loads since EAFs operate in batches and can be started up or shut down relatively quickly, unlike traditional continuous furnaces. Their electrical power source allows them to adapt to fluctuating electricity availability or pricing, making them ideal for use with intermittent renewable energy and participation in demand response strategies.
- EAF is the most common way of producing secondary (recycled) steel from steel scrap feedstocks. EAFs are also used in the production of high-grade [alloy steel](#), aluminium, copper, lead and other metals (Perera and Elphick, 2023)

### Metal Industry

- EAF is the most common way of producing secondary (recycled) steel from steel scrap feedstocks.
- It can be used to smelt high-quality steel and other special steels.
- Capable of producing the full range of steel grades
- EAFs are also used in the production of high-grade alloy steel, aluminium, copper, lead and other metals



### BENEFITS

- Thanks to advancements in related technologies, electric arc furnaces can now be well-integrated into traditional steel-making operations.
- EAFs are an alternative to conventional blast furnace steelmaking, one of the most carbon intensive industries.
- EAFs offer faster and more flexible operation, as they run in batch mode and can be started or stopped more quickly than traditional steelmaking processes.



### CHALLENGES

- EAFs require a massive and stable electricity demand. If not paired with significant RES capacity onsite leads to high energy costs and puts stress on the electricity grid, especially during rapid power fluctuations that may cause voltage dips
- Graphite electrodes in EAFs degrade over time due to high-temperature cycles and chemical exposure, making electrode wear a significant operational cost.

## ELECTRIC ARC FURNACE (EAF) (CONT.)

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### **BENEFITS** (CONT.)

- They are also better suited for grid-responsive operation or integration with renewable electricity, making them adaptable to fluctuating power availability.
- Electric Arc Furnaces require a smaller plant footprint compared to conventional blast furnace-based steelmaking routes, allowing for more compact facility designs.
- Modern EAFs can achieve high energy efficiency, particularly when equipped with energy recovery systems and advanced process controls.



### **CHALLENGES** (CONT.)

- EAFs present environmental challenges such as particulate and fume emissions, as well as noise and light pollution; therefore, appropriate safety and health measures must be taken to protect workers and comply with environmental standards.

## 2.4.7 PLASMA HEATING

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### WORKING PRINCIPLE

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Plasma heating, typically through plasma torches or plasma furnaces, involves the conversion of electricity into heat by generating and using ionised gas (plasma). This plasma is produced using an electric arc: a continuous discharge of electricity between two electrodes through a gas. The arc provides intense energy that ionises the gas, turning it into plasma. The resulting plasma can reach extremely high temperatures and is used to heat or melt materials directly.

Nowadays, plasma heating systems can reach capacities of up to 8 MW, with an efficiency that ranges between 50% and 90%, depending on the specific setup and application.

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### HEAT GRADE

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Suitable for high-grade heat applications only, with a temperature range up to 5000 °C, depending on the plasma system used.

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### APPLICATIONS

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- Thermal plasmas can be implemented in a broad range of engineering applications where very high temperatures, fast heat transfer, or clean processing are needed. It can also be used for very specialised applications.
  - The major area of industrial applications of plasma heating is the metallurgical sector, and in particular steel making. Low power-plasma can also be used for cutting and welding and powder spraying, which is an established industry. However, the other high-power applications have garnered significant attention globally and specifically in the domain of environment (Retech, no date).
-

## PLASMA HEATING (CONT.)



### APPLICATIONS (Cont.)

#### Metal Industry

- Melting of iron, steel, nickel alloys in ceramic crucibles or open hearths
- Thermal plasma has been applied for heating of metals in ladle and tundishes of continuous casters in steelmaking process.
- Plasma arc remelting and surface treatment, used for cleaning and refining ingots, removing defects, and improving surface properties.

#### Cement Industry

- Sinter of cement clinker

#### Chemical Industry

- Thermal plasma torches and furnaces are used for producing high-purity metals and for nanoparticles synthesis



### BENEFITS

- Can often be automated, which not only saves time but also enhances consistency and efficiency.
- Very fast ramp-up rates and efficient energy transfer to materials.
- Delivers focused heat to a specific zone, reducing energy waste and improving process control.
- Electric, high-temperature alternative to fuel counterparts as oxy-fuel burners and fossil-fuel furnaces
- Can operate in oxidising, reducing, or inert atmospheres, allowing treatment of sensitive or reactive materials.



### CHALLENGES

- Complex system requirements that entail safety measures in place for handling very high temperatures and ionised gases.
- High electrode wear that lead to added maintenance costs and downtime for replacement
- In some cases, integrating into older or non-electric systems can require significant retrofitting and redesign.

## 2.5 Heat Storage technologies

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Heat storage technologies can be categorised in three broad categories, depending on the governing principle of operation (Sarbu and Sebarchievici, 2018), (Zhao et al., 2023), (Mahon and Eames, 2020)

1. Sensible Heat Storage
2. Latent Heat Storage, &
3. Thermochemical Heat Storage

### 2.5.1 SENSIBLE HEAT STORAGE (SHS)

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#### WORKING PRINCIPLE

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**Sensible Heat Storage systems utilize the heat capacity and the change in temperature of the storage medium during the process of charging and discharging.**

There are several types of heat storage media within the sensible heat storage category, available in both liquid and solid forms. Common liquid media include water, mineral and synthetic oils, and solar salt (a molten salt mixture suitable for high-temperature applications). Common solid media include cast steel, reinforced concrete, crushed rock, and sand.

Among these, the most widely used are water for low- to medium-temperature systems, and reinforced concrete, crushed rock, and sand for solid thermal storage, particularly in high-temperature or bulk applications.

For a given volume of sensible heat storage medium, the amount of heat that can be stored depends on the temperature range, as well as on the specific heat capacity and the density of the storage material (Ho and Ambrosini, 2021).

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## WATER

Water is one of the most effective liquids for storing heat per unit mass, being a well-developed storage medium used in diverse applications, from domestic hot-water storage to district heating systems.

Maximum storage temperatures for water is limited to ~ 90 °C, for non-pressurised systems, and to ~ 150 °C, for pressurised systems.

Water has a specific heat capacity of approximately 4.2 kJ/ kg·K and a density of 1000 kg/m<sup>3</sup>.



### BENEFITS

- Inexpensive and non-toxic
- Well established and proven as heat storage medium
- Highly efficient when well insulated and stratified
- Very high heat capacity



### CHALLENGES

- Inexpensive and non-toxic
- Well established and proven as heat storage medium
- Highly efficient when well insulated and stratified
- Very high heat capacity

## OILS

Thermal transfer oils are widely used in industrial systems. Mineral and synthetic heat-transfer oils remain liquid at atmospheric pressure up to much higher temperatures than water, enabling medium-temperature heat storage, without a pressurized vessel. Mineral oils can operate on temperature ranges between ~ 250 and 300 °C, while the operational temperature range of synthetic oils is between ~ 250 and 400 °C.

Oils have a specific heat capacity between 2 and 2.5 kJ/kg·K, and an approximate density of 880 kg/m<sup>3</sup> depending on the specific type of oil.



### BENEFITS

- Relatively high temperature range
- Well established and proven as heat storage medium
- Enable medium temperature heat storage
- Easy to integrate with heat exchangers and transfer systems



### CHALLENGES

- Low volumetric heat capacity
- Operation near their upper limit temperatures can cause chemical decomposition, increased viscosity, and flammability hazards
- Safety and environmental concerns (leaks, fires) must be managed

## SOLAR SALTS

Solar salt is a mixture of sodium nitrate ( $\text{NaNO}_3$ ) and potassium nitrate ( $\text{KNO}_3$ ), commonly used as a high-temperature heat transfer and storage medium. The name comes from its widespread use in concentrated solar power (CSP) plants (Urbanczyk et al., 2017).

Operates at high-grade heat, with a typical temperature range from around 260 °C to 560 °C.

Solar salt has a specific heat capacity of ~1.5 kJ/kg·K (approximate value at 300 °C, increasing slightly with temperature) and a high density of ~1800–1900 kg/m<sup>3</sup>.



### BENEFITS

- Non-flammable and relatively inexpensive
- High volumetric heat capacity due to a combination of high density and high specific heat
- Remains liquid over a broad high-temperature range
- Use and performance are well demonstrated in CSPs applications, making it a promising option for other high-temperature heat storage applications



### CHALLENGES

- High melting point: must be kept at high temperatures to avoid crystallisation
- Compatibility with container materials may be an issue, as it can be corrosive to certain steels (expensive alloys or additives may be needed for long-term stability)
- Upper temperature limits must be respected, since after a certain temperature threshold nitrate salt begins to decompose, releasing corrosive gases

## CAST STEEL

Solid cast steel (or cast iron) can serve as a very high-temperature heat storage medium.

Cast steel can operate over a wide temperature range, typically between 200 and 700 °C, depending on the grade and containment materials. The high thermal conductivity of steel allows efficient charging and discharging of thermal energy. However, care must be taken to avoid oxidation and thermal fatigue, particularly at the upper range of temperatures.

Cast steel offers high volumetric heat capacity due to its reasonable specific heat capacity of ~0.5 kJ/kg·K and high density of 7800 kg/m<sup>3</sup>.



### BENEFITS

- High volumetric heat capacity due to high density
- Suitable for high-temperature applications (up to ~700 °C)
- High thermal conductivity allows efficient charging/discharging
- Mechanically robust



### CHALLENGES

- High cost compared to other solid media
- Oxidation and thermal fatigue at high temperatures
- Requires corrosion-resistant containment materials
- Heavy, requiring structural support in system design

## REINFORCED CONCRETE

Reinforced concrete is a relatively affordable and scalable material for medium-grade sensible heat storage. It is used in large-scale storage systems due to its structural properties, but thermal cracking and low thermal conductivity (~1–2 W/m·K) can be limitations.

Concrete can store heat in a temperature range from 100 to about 400 °C. Above 400 °C, standard concrete starts to degrade, so specialised high-temperature mixes are needed.

It has a specific heat capacity around 0.85–0.9 kJ/kg·K and a density of approximately 2200 kg/m<sup>3</sup>.

### ▶▶ BENEFITS

- Low cost and easy scalability
- Structurally stable and easy to shape into large blocks
- Compatible with medium-temperature storage (up to ~400 °C)
- Suitable for integration with embedded heat exchangers

### || CHALLENGES

- Thermal conductivity is relatively low
- Risk of thermal cracking during repeated cycling
- Above ~400 °C, material degradation occurs unless special formulations are used
- Heavier systems require robust foundations and insulation

## CRUSHED ROCK

Crushed rock or gravel, typically basalt, granite or ceramic, is a low-cost, high-temperature storage medium used in packed-bed systems. Rock beds are thermally stable and inexpensive, though they require good insulation and airflow control to minimize losses and pressure drops.

The operating temperature range is typically between 100 and 600 °C, with some systems reaching up to 750 °C depending on the rock type and containment.

It has a specific heat capacity between 0.8 and 1.0 kJ/kg·K and a bulk density of approximately 1600–1800 kg/m<sup>3</sup>.

### ▶▶ BENEFITS

- Inexpensive and widely available material
- Thermally stable up to ~600–750 °C
- Good for bulk thermal storage with air-based heat transfer systems
- Can be used in simple packed-bed configurations

### || CHALLENGES

- Irregular shape and size can affect packing density and heat transfer
- Lower volumetric heat capacity compared to denser materials
- Requires good insulation and airflow management to minimise losses

## SAND

Sand, particularly dry silica sand, is another low-cost, high-temperature sensible heat storage material. It is thermally stable and chemically inert, making it suitable for high-temperature systems such as resistive heating. Sand can be used in static beds or moving systems and is currently being explored for large-scale, long-duration storage applications.

Sand has a specific heat capacity that ranges from ~0.8 to over 1.5 kJ/kg·K depending on temperature, and a bulk density of around 1600–1700 kg/m<sup>3</sup> (Focal Line Solar Inc., 2024).



### BENEFITS

- Extremely low cost and abundant
- Can operate over a very broad temperature range (ambient to 1000+ °C)
- Chemically inert and thermally stable at high temperatures
- Suitable for long-duration storage and large-scale systems



### CHALLENGES

- Moderate thermal conductivity and non-uniform grain size can affect performance
- Requires careful design to ensure even heat distribution and recovery
- Settling and compaction may occur over time in static systems
- Dust management and containment are important for high-temperature operation

## 2.5.2 LATENT HEAT STORAGE (LHS)

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### WORKING PRINCIPLE

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**Latent Heat Storage (LHS) materials are also known as Phase Change Materials (PCM) due to their property of releasing or absorbing energy with a change in physical state, typically from solid to liquid or vice versa.**

During this phase change, heat is absorbed or released at a nearly constant temperature, corresponding to the material's latent heat. This results in a high energy storage density, allowing more heat to be stored in a smaller volume compared to sensible heat systems. LHS systems using PCMs are considered effective for thermal energy storage due to their isothermal behaviour during charging/discharging and their compact design potential.

There are several types of PCMs, including organic PCMs, such as paraffin and non-paraffin compounds; and inorganic PCMs, like salt hydrates. Among these, paraffin waxes and salt hydrates are the most commonly used (Kulish et al., 2023).

For a given volume of a PCM, the amount of heat that can be stored depends on the material's latent heat of phase change and its density.

Most commercially available PCMs nowadays are designed for low to medium temperature ranges, typically between 20 °C and 150 °C. Some high-temperature PCMs (e.g. metal alloys, molten salts) do exist and can reach >300 °C, but these are less common and more technically demanding.

When the PCM solidifies, it releases heat at a nearly constant temperature. This heat can be extracted by heat exchangers (metal surfaces, fins, or embedded tubing) that transfer the PCM heat to a circulating fluid, usually water or air. In some designs, the PCM is enclosed in containers that are placed near or around the heat demand area, transferring the heat through direct contact (Number Analytics, 2025).

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## PARAFFIN WAX (ORGANIC PCM)

Paraffin wax is one of the most commonly used PCMs for latent heat storage, widely applied in thermal energy storage systems (e.g. solar heating units, building heat storage) and even electronics cooling.

It typically melts within a moderate temperature range (often between ~45–70 °C, though some formulations range from ~6 °C up to ~108 °C), which places it in the low-grade heat category (useful for storing heat below ~100 °C).

Upon melting, paraffin absorbs a large amount of heat at nearly constant temperature and releases it upon solidifying.

Paraffin wax has a latent heat of fusion on the order of ~200 kJ/kg and a density around 800–950 kg/m<sup>3</sup>, giving it a high energy storage capacity per unit mass (though a lower energy density per unit volume than some inorganic materials).

Paraffin wax PCMs are commonly used in building systems, solar thermal storage, and temperature control for electronics and packaging in various industrial settings ('Paraffin Wax PCM Heat Sinks Transient Thermal Storage for Electronics Cooling', no date).

## ▶▶ BENEFITS

- High latent heat capacity (typically ~200 kJ/kg)
- Chemically inert and non-corrosive, which means it does not corrode containers and is compatible with most materials
- Non-toxic and safe to handle
- Reliable cycling and phase stability
- Well-established and widely available being commercially available in many formulations covering various melting points

## || CHALLENGES

- Paraffin wax is combustible and has a relatively low flash point (~200 °C), so it can't be used for very high-temperature heat storage and poses a fire risk if overheated
- Low thermal conductivity (~0.2 W/m·K): heat transfer into and out of the wax can be slow
- Low volumetric energy density (0.9 g/cm<sup>3</sup>) storing less energy per unit volume
- Moderate cost due to proper enclosures to avoid leakage

## SALT HYDRATES

Salt hydrates are inorganic PCMs consisting of a salt and water of crystallization, and are among the most common latent heat storage media. A well-known example is sodium sulfate decahydrate ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ), also called Glauber's salt, which has a melting point of around 32 °C.

In general, salt hydrates suitable for heat storage melt in a range roughly from ~20 °C up to around 80 – 90 °C depending on the composition. This allows storage of low-grade thermal energy at those phase-change temperatures. During melting, the hydrate salt absorbs heat as it converts from a hydrated solid to a slurry or liquid and releases the heat upon crystallization.

Sodium sulfate decahydrate, for instance, has a high latent heat of fusion on the order of 240–250 kJ/kg. Salt hydrates are generally quite dense – Glauber's salt has a solid density of about 1460 kg/m<sup>3</sup>, so these materials can store a large amount of energy in a compact volume.

These PCMs have been used in applications like passive solar heating systems, building thermal regulation (e.g. wall or ceiling panels with PCM), and waste-heat recovery, thanks to their cost-effectiveness and safety.

## ▶▶ BENEFITS

- High latent heat storage capacity due to very high heats of fusion
- High storage capacity due to high energy density per volume
- Inorganic hydrated salts are usually inexpensive and relatively abundant, being derived from common salts and water
- Non-flammable and safe

## || CHALLENGES

- Many salt hydrates are corrosive to common metals, requiring a careful choice of containment or addition of corrosion inhibitors, increasing costs
- Potential phase stability issues and phase separation: the material may not solidify and release heat reliably, or it may lose storage capacity after many cycles
- Volume change on phase transition that can cause mechanical stress or require extra space in the container
- Leakage and evaporation if not properly sealed

## 2.5.3 THERMOCHEMICAL HEAT STORAGE (TCHS)

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### **WORKING PRINCIPLE**

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**Thermochemical heat storage (TCHS) is another form of thermal energy storage that differs from sensible and latent systems by relying on reversible chemical reactions to store and release heat.**

In these systems, thermal energy is used to drive an endothermic reaction (e.g. dehydration or dissociation), and heat is recovered when the reaction is reversed. This approach allows for very high energy densities and long-term storage without thermal losses, as the energy is stored in the chemical bonds of separated reactants. However, despite its promising potential, thermochemical heat storage is not yet widely deployed at industrial scale. It remains largely in the research or pilot stage, due to challenges such as slow response times, system complexity, and the need for precise control of temperature, pressure, and materials handling.

For this reason, while TCHS is briefly noted here for completeness, it is not covered in detail alongside the more commercially mature technologies (Desai et al., 2021).

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## 2.6 Summary

No single technology or policy can fully electrify all industrial processes, given the sector’s complexity and the diversity of its subindustries. However, a broad set of all-electric technologies is available that can meet a wide spectrum of temperature requirements across various industrial applications (**Table 4**). These solutions, when strategically

combined and matched to specific process needs, offer a realistic pathway to reduce fossil fuel dependence, improve energy efficiency, and support the decarbonisation of industry. The right mix will depend on technical, economic, and policy factors—highlighting the importance of tailored approaches and continued innovation.

**Table 4:** Summary table of technologies across industry investigating Power to Heat and Heat Storage solutions.

Heat grade	Industry	Industry processes	Heating Tech.
	<b>Metal</b>	Pre-heating, heating, hardening, tempering, welding, annealing. Heat treatment (annealing, tempering, preheating), Soldering and brazing, Forging, Metal melting	Induction, Electric Arc, Plasma, Resistance
	<b>Cement</b>	Crushing, grinding, preheating, calcination,	Plasma
	<b>Lime</b>	Calcination, decarbonation, Preheating, Drying	Plasma, Electric Arc
	<b>Other Minerals</b>	Kiln drying, Melting, Firing, Vitrification, Calcination, Preparation, Property enhancement, Tempering, Curing of Glass fibre, Curing of Rock Fiber	Electric resistance, Infrared, Heat Pumps, Induction, Microwave, RF Heating
	<b>Refining</b>	Steam reforming, Cracking, Heating of reactors and vessels, Distillation	Electric resistance,
	<b>Chemical</b>	Boiling, Distilling, Drying, Cracking, Pyrolysis, Reacting, Steam reforming, Sterilising, Drying active pharmaceutical ingredients (APIs), Microwave-assisted synthesis (MAS), Sterilisation of sensitive products	Electric resistance, Microwave, RF, Resistance, Infrared
	<b>Wood products</b>	Wood drying, Moisture control, Pressing, Curing, Heat treatment, Thermal modification, Dehumidification and drying pulp/paper, textiles	Heat pump, Electric resistance
	<b>Food and Drink</b>	Mashing, UHT, boiling, baking, frying, cooking, drying, pasteurising, evaporating, Drying and dehydration, Pasteurisation/sterilisation	Heat pump, Electric resistance, Microwave, Infrared, RF
	<b>Other</b>	Heat treatment, Drying herbs, grains, and biomass; Inactivation of pests or pathogens; Wastewater evaporation	Heat pump, Electrical resistance, Microwave

# Section 3: Industry

## Examples: P2H and TES Technologies

### 3.1 Overview of the Industry's Need for Heat

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Globally, industrial heat accounts for a significant portion of both energy demand and emissions. In Ireland alone, total heat demand reached 48.4 TWh in 2023, with the industrial sector accounting for 35.8% of that demand (approximately 17.3 TWh) (SEAI, 2024c). Over 90% of industrial heat in Ireland still comes from fossil fuels, even as renewable heat use rose modestly to 8.0% of total heat in 2023, with ambient heat pumps contributing nearly 29% of that (SEAI, 2024a).

According to the SEAI, in 2023, Metals was the sector responsible for the highest amount of heat consumption, reaching approximately 4500 GWh, and followed by the Food & Drink and the Cement sectors that consumed, respectively, around 3500 and 2900 GWh of heat. When viewed alongside their economic significance, these high heat-consuming sectors reveal different dynamics in Ireland's industrial landscape. In 2023, the Food Products sector recorded a Net Selling Value (NSV) of €23.7 billion, 17.2% of the total industrial output. In the same year the Metals sector reported an NSV of €5.7 billion. The substantial heat demand of the Food Products and Metals sectors partly reflects their significant presence in the economy. In contrast, the Cement sector, with a much smaller economic output of approximately €181 million, still ranks among the top 3 industrial heat users, highlighting the inherently energy-intensive nature of cement production rather than its market size in Ireland (CSO, 2023)<sup>4</sup>.

Heat demand varies greatly across industries and as such, heat demand is graded to allow for easier classification of industry heat demands (Table 5).

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<sup>4</sup> Note: Sector classifications used by the Central Statistics Office (CSO) and the SEAI are not directly aligned. As a result, data comparisons between economic output and energy use are approximate and based on best-fit categorisations.

**Table 5:** Heat classification table with an overview of percentage of total industry demand (adapted from SEAI National Heat Study (National Heat Study-SEAI, 2022))

Heat classification	Temperature range	% Of total industry demand
LOW	<100°C	~8%
LOW-MEDIUM	100-150°C	~32%
MEDIUM	150-500°C	~35%
HIGH	>500°C	~26%

Sectors such as Wood Products, Food and Drink, Chemicals, and Other Industry require mostly low to medium grade heat, while the Metal, Cement, Lime and Refining sectors rely primarily on medium and high-grade heat for their processes.

### 3.2 Overview of Identified Case Studies

This study conducted a cross-sectoral analysis of 31 case studies where Power to Heat and/or heat storage technologies were applied in the industry manufacturing processes. The case studies focused on power to heat strategies and their applications in the manufacturing process. Understanding

current industrial practices is essential to identifying where Power to Heat can realistically be applied today. This is also necessary to look at the state of the art to benchmark the full technical potential of Power to Heat solutions for the future.

**The case studies profiled are categorised by the following sectors.**

1. Metal Industry
2. Cement Industry
3. Refining Industry
4. Wood Products Industry
5. Other Minerals Industry
6. Food and Drink Industry
7. Lime Industry
8. Chemical Industry
9. Other Industry

In the subsequent pages, Power to Heat and Heat Storage technologies are studied across the industry, based on the identified industry sectors above. It is evident that high heat grade sectors are at an inflection point regarding current technology. Industries are undergoing significant technological developments, with emerging commercialised technologies, to retrofitting of old systems to boost performance and extend the lifespan of installed technologies. Industries will need to

decide whether to retrofit or renovate their production lines.

These 31 case studies are summarised in Table 6. The table aims to categorise industries by their heat grades and demonstrate the specific Power to Heat and Heat Storage technologies most prominent across the heat grades. This also indicates which technologies may be opportune for companies seeking to transition to the Power to Heat technologies.

**Table 6:** Summary table of case studies across industry investigating Power to Heat and Heat Storage solutions.

Case Study	Industry	Industry process	Heat Grade	Heating Tech.	Heat Storage Tech.	Heat medium	Material heated
1	Metal	Heating, rolling	High	Induction	-	Direct heating of material	Steel, Iron, Aluminium, metal billets,
2	Metal	Metal thermal treatment	High	Infrared	-	Direct heating of material	Steel
3	Metal	Furnace heating	High	Electric Arc	-	Direct heating of material	Steel, Iron, Aluminium, metal billets,
4	Cement	Furnace heating	High	Plasma heating	-	Gas (Plasma)	Limestone, shale, stones
5	Cement	Furnace heating	High	Friction based	-	Gas	Metals, stone
6	Refining	Steam Cracking	High	Electric resistance	-	Direct heating of material	Naphtha, crude oil, ethane
7	Refining	Steam supply for plant	High	Electric resistance	-	Direct heating of material	Alumina
8	Refining	Steam for microturbine	High	-	Sensible Heat	-	(Thermal oil)*
9	Wood Products	Pre-heating of material	Low, Low-medium, Medium	Heat pump	-	Air	Timber
10	Wood Products	Pre-heating of material	Low, Low-medium, Medium	Heat pump	-	Air	Timber
11	Wood Products	Pre-heating of material	Low	Infrared	-	Direct heating of material	Timber
12	Other Minerals	Glass smelting	Low-medium, Medium, High	Electric resistance	-	Direct heating of material	Glass
13	Other Minerals	Brick firing, Drying	Low-medium, Medium, High	Heat pump	-	Air	Bricks
14	Other Minerals	Smelting, firing	High	Electric resistance, induction, microwave, Heat pump	Sensible Heat	Direct heating of material, Gases	Frit, bricks, rocks (Ceramic Waste)*
15	Food and Drink	Boiling, heating	Low-medium, Medium	Heat pump	-	Air	Water
16	Food and Drink	Boiling, heating, pasteurisation, sterilisation	Low-medium, Medium	Electric resistance, Heat pump	-	Direct heating of material, Air	Water
17	Food and Drink	Boiling, heating	Low-medium, Medium	-	Sensible Heat	-	(Crushed rock)*
18	Food and Drink	Boiling, heating, pasteurisation, sterilisation	Low-medium, Medium	Heat pump	-	Air	Milk, dairy

Case Study	Industry	Industry process	Heat Grade	Heating Tech.	Heat Storage Tech.	Heat medium	Material heated
19	Food and Drink	Boiling, heating	Low-medium, Medium	-	Sensible Heat	-	(Crushed rock)*
20	Food and Drink	Heating	Low	Microwave	-	Direct heating of material	Fruit pits
21	Lime	Calcination	High	Plasma heating	-	Gas (Plasma)	Limestone, shale, stones
22	Lime	Calcination	High	Electric resistance	-	N/A	Limestone, shale, stones
23	Chemical	Heating, drying	Low-medium, Medium	-	Sensible Heat	-	(Crushed rock)*
24	Chemical	Grid balance, boiling	Low-medium, Medium	-	Sensible Heat	-	(High-pressure steam)*
25	Chemical	Preheating, drying	Low-medium, Medium, High	Electric resistance	Sensible Heat	Direct heating of material	(Thermal storage bricks)*
26	Chemical	Drying	Low	Microwave	-	Direct heating of material	Adhesive
27	Other	Drying	Low	Microwave	-	Direct heating of material	Coating
28	Other	Drying	Low	Infrared	-	Direct heating of material	Latex
29	Other	Drying	Low	Microwave	-	Direct heating of material	Polyamide
30	Other	Heating, drying, curing	Low-medium, Medium	-	Sensible Heat	-	(Crushed rock)*
31	Other	Heating, Steam production	Low-medium, Medium	-	Sensible Heat	-	(Thermal storage bricks)*

\* Storage Material

## PLEASE NOTE

Because of the difference in measurement and evaluation techniques and methodologies it would be impossible in the scope of these guidelines to provide an accurate verification or comparison of information presented in the case studies below.

The information presented is taken from company source material publicly available on the companies' website, or from websites of third parties.

The accuracy of this information is taken in good faith and the presence of this information in the case studies does not constitute a verification of the accuracy of this information or an endorsement of the company or any commercially available technologies.

### 3.3 Heat Use in the Metals Industry

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In Ireland, the metal industry broadly encompasses two main categories:

1. Ferrous metals, primarily in the steel sector, which include steelmaking, fabrication, structural steel, reinforcement bars, and finished steel products such as girders and frameworks.
2. Non-ferrous metals, such as aluminium, copper, zinc, and lead, encompassing activities from extraction (mining and refining) to processing and manufacturing of downstream products.

In the metal industry, heat is commonly produced using electric arc furnaces (EAF), gas-fired furnaces, and induction furnaces. It is essential in processes such as Steam generation, the Bayer process, Calcination, Rolling, Melting, Sintering, Melting and other high temperature processes. It enables phase changes, drives chemical reactions, softens or fuses materials, and facilitates shaping, bonding, and extraction in high-temperature operations.

The metal industry relies on high grade heat (>500°C) and medium grade heat (150 - 500°C).

### 3.4 Metal Industry Case Studies

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#### 1. REBAR MILL MODERNIZATION AT FERALPI GROUP, ITALY

**HEAT GRADE:** HIGH

**TECHNOLOGY:** INDUCTION HEATING

In September 2023, the billet reheating furnace at the plant was dismantled in favour of a Power to Heat electrically powered induction heating system. Due to the nature of the process, the induction furnace only operates when the metal passes through the furnace. With the upgrade and transition to Power to Heat, Feralpi Group successfully upgraded the process within the plant to operate continuously, with an uninterrupted flow of billet (semi-processed metal). With the upgrade of the plant the group was able to eliminate direct CO<sub>2</sub> emissions within the plant through the elimination of the gas-fired furnace. The study demonstrated that the retrofit of existing brownfield plants with revolutionary modern technology can aid in the decarbonisation of these emission and energy intensive industries (SMS group GmbH, 2024).

## 2. FRANK Walz- und Schmiedetechnik GmbH, Germany

**HEAT GRADE:** MEDIUM

**TECHNOLOGY:** INFRARED

FRANK Walz and Schmiedetechnik GmbH, a specialist in wear protection for agricultural machinery, needed to improve the thermal treatment of quenched and tempered steels. Traditional thermal treatment was time-consuming for adjusting material properties. In a project supported by EU funding, an innovative infrared tempering process was developed along with a calculation model to determine the minimum heating and holding times needed for different steels to achieve desired properties. The new process led to improved press-hardened steel components with excellent material properties and a very good energy balance. The system used short-wave infrared emitters with a power density of up to 100kW/m<sup>2</sup>. The new process has optimized the energy efficiency of the process. ('NobleLight', 2025)

## 3. STEGRA BODEN STEEL PLANT, SWEDEN

**HEAT GRADE:** HIGH

**TECHNOLOGY:** ELECTRIC ARC FURNACE (EAF)

Scheduled for production in 2026, the Boden Green Steel project is a lighthouse project taking place in the town of Boden, just 72km south of the Arctic circle. The project is a first of its kind, utilising not only Power to Heat, but also Power-to-X-to-heat<sup>5</sup> technology. An 800MW electrolyser will use renewable electricity to produce enough H<sub>2</sub> to process 5 million tons of high-quality steel by 2030. The H<sub>2</sub> will be used in the Direct Reduced Iron (DRI) (800-1200°C) process, reducing CO<sub>2</sub> emissions by 95%. Meanwhile an Electric Arc Furnace (EAF), using renewable electricity to further heat the DRI, will transform the iron to steel. Instead of using natural gas, as is traditionally used, the plant will use a continuous casting and rolling process to reduce the process energy consumption by 70% (Midrex Technologies, Inc., 2021).

<sup>5</sup> Power-to-X-to-Heat: Refers to the conversion of excess renewable electricity (like wind or solar) into other forms of energy, including heat, hydrogen, and synthetic fuels.

### 3.5 Heat Use in the Cement Industry

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The cement industry primarily focuses on the production of different types of cement, most commonly Portland Cement. This process involves the extraction and processing of raw materials such as limestone, clay, marl, gypsum and shale, before being crushed, heated and ground down. Within this industry heat comprises much of the energy demand. Fossil hydrocarbons (such as coal, natural gas or oil) are traditionally used as an energy source to heat large rotary kilns, to dry

material, and to enable calcination and clinkerisation processes. These processes enable lime decarbonation and the high-temperature reactions which form clinker.

The cement industry needs high grade heat (>800 °C for clinkerisation), and medium grade heat (150 – 800 °C for drying and preheating) (IEA, 2018), making it one of the hardest industries to decarbonise.

### 3.6 Cement Industry Case Studies

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#### 4. ELECTRA PROJECT, SWEDEN

**HEAT GRADE:** HIGH

**TECHNOLOGY:** PLASMA HEATING

The innovative ELECTRA project explores Power to Heat technologies to displace the traditional combustion processes used in the cement industry. The project has successfully tested the electrification of cement production using a plasma-heated cement kiln. This kiln reduces both energy demand and carbon emissions compared to conventional kilns. By reducing CO<sub>2</sub> emissions up to 90%, the plasma-heated kiln can significantly reduce the need for investment in CO<sub>2</sub> sequestration across the production chain. The CO<sub>2</sub> gas is converted to a plasma jet, capable of heating material to over 2000 °C in the kiln. This eliminates fuel related CO<sub>2</sub> emissions from the process. The absence of fuel also results in an absence of ash, which might otherwise reduce the quality of the clinker produced. Currently a 300 kW<sub>el</sub> furnace in Slite acts as a pilot system, and a 1 MW<sub>el</sub> furnace is being built in Skövde to a demonstration level, where tests will continue in 2027. Some of the by-product CO<sub>2</sub> from the cement production process (calcination) is captured at a low cost and reused for the plasma, while the rest is processed for geological storage (ELECTRA, 2025).

## 5. COOLBROOK, ROTODYNAMIC HEATER (RDH), GELEEN, NETHERLANDS

**HEAT GRADE:** HIGH

**TECHNOLOGY:** FRICTION-BASED HEATING

Coolbrook has developed a novel high-heat grade industrial process heater, enabling a Power to Heat solution for high-grade heat. By using clean electrification to reach temperatures of up to 1700 °C, the novel friction-based heating technology proposes a green alternative to conventional industrial heating. The technology functions by heating gases (typically air) using a novel electrically powered turbine technology, designed to heat gas through friction. The gases reach a high temperature within the turbine before being used to heat the material. As the turbine is electric, this process displaces traditional fossil fuel use. The technology can be used to electrify steel, iron, cement and chemical production lines and is currently undergoing commercialisation, with the first units being delivered in 2025. The company is also launching a system for electrified steam reformation and electrification of the refining industry (Coolbrook, 2025).

## 3.7 Heat Use in the Refining Industry

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The refining of crude oil involves refineries and petrochemical plants transforming raw hydrocarbons (naphtha, crude oil) into an array of products (gasoline, diesel, jet fuel, lubricants, and chemical feedstocks). Heat is critical across most refining processes, traditionally generated through fired heaters and furnaces combusting various fuels (refinery off-gas, natural gas, fuel oil), as well as steam boilers, Heat Recover Steam Generation (HRSG) and air preheaters. Heating is essential for processes like

crude oil distillation, catalytic cracking, hydrocracking, reforming, visbreaking, product stream preheating and stabilisation. Heating allows for the phase separation of hydrocarbons, driving complex chemical conversions, and is crucial for temperature maintenance for optimal reactions.

The refining industry relies on high grade heat (>350 °C) in the distillation and cracking processes, and medium grade heat (150 – 350 °C) for preheating application.

## 3.8 Refining Industry Case Studies

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### 6. BASF'S LUDWIGSHAFEN CHEMICALS COMPLEX, GERMANY

**HEAT GRADE:** HIGH

**TECHNOLOGY:** ELECTRIC RESISTANCE HEATING

A BASF plant in Germany has implemented a first of its kind demonstration using electric resistance heating. The plant demonstrates continuous production of olefins, via Power to Heat means such as electric Steam Cracking Furnaces<sup>6</sup> (>850 °C). This cuts emissions from the foundational process by 90%. The demonstration plant uses two electric heating methods. One furnace applies an electric current to the cracking coils, and the second furnace uses heating elements utilising radiative heat transfer to supply the thermal energy necessary to break down the feedstock passing through the furnace. This novel demonstration was integrated into the existing cracking systems at the site. Between the two furnaces, approximately 4 tons of hydrocarbon feedstock are being processed per hour, consuming 6 MW of renewable energy. The demonstration results currently indicate that the price of renewable electricity dictates the commercialisation of the project (IChemE, 2024).

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<sup>6</sup> 'Cracking' refers to the breaking down of molecules (like naphtha or ethane) into more valuable molecules like olefins, aromatics, ethylene and propylene using high temperatures and steam. The term is prevalent in the Refining Industry, which involves the breaking down of strong covalent bonds of molecules, effectively "Cracking" them.

## 7. VAUDREUIL ALUMINA REFINERY, SAGUENAY, CANADA

**HEAT GRADE:** HIGH

**TECHNOLOGY:** ELECTRIC RESISTANCE HEATING

In 2018, the Vaudreuil alumina refinery struck a deal with the local hydroelectric producer to develop a Power to Heat solution. This led to the continuous operation of three electric boilers, operating with over 80% uptime. The boilers supplied 35% of the total steam demand of the plant using electric resistance heating. The revamp has contributed to reducing CO<sub>2</sub> emissions by 21% per ton of calcinated alumina produced. The conventional gas boilers operated in tandem with the electric boilers. Due to the direct heating of water through resistance heating, the boilers produce steam at almost 100% efficiency, avoiding traditional heat losses associated with fossil fuel boilers (Reid, 2024).

## 8. ENI S.P.A. REFINERY, SICILY, ITALY

**HEAT GRADE:** MEDIUM

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

The Eni S.p.A. refinery in Italy set an objective of integrating Heat storage technology into its oil refinery process. The project utilised concentrated solar power (CSP) and a sensible heat storage unit using ThermalBattery™ technology. This technology employs a solid-state high temperature energy storage system that uses thermal oil or steam as a heat-transfer medium for charging and discharging thermal energy on demand. The stored thermal energy is used to produce steam to spin a micro turbine onsite, allowing for the stable production of electricity at night. This system saved the site 60 tCO<sub>2</sub>/a (EnergyNest, 2019).

### 3.9 Heat Use in the Wood Products Industry

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The wood products sector spans diverse activities involving the transformation of raw wood from trees into useful materials and goods. It starts with harvesting timber from forests, which is then processed into products like lumber for construction, plywood and particleboard for furniture, and pulp for paper. These materials are used to make everyday items such as furniture, flooring, packaging, and more.

Within this industry, heat is traditionally generated through the combustion of biomass (timber waste, bark, sawdust etc.) in biomass boilers and furnaces, thermal oil heaters, steam boilers, CHP or direct fire dryers. Electric heating methods such as resistance heating

may be employed in specific applications.

In the wood products sector heat is used in a variety of processes: wood drying to lower moisture content; pressing and curing used in the production of certain products (such as Oriented Strand Boards (OSB) or plywood); heat treatment (for resin or adhesive setting); timber thermal modification which is used to enhance the physical, chemical, and stability properties of wood; amongst others.

The industry relies on medium grade heat (150 – 500 °C) for drying and pressing processes, and thermal modification processes (160 – 260 °C).

### 3.10 Wood Products Industry Case Studies

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#### 9. SWISS KRONO - ZARY FACILITY, POLAND

**HEAT GRADE:** LOW, LOW-MEDIUM

**TECHNOLOGY:** HEAT PUMP

The Zary facility for the Swiss Krono OSB board manufacturer, faced a challenge at their facility in Poland when the existing dryer struggled to reduce the moisture content of the OSB board strands from 50% to 2%. This limited the production capacity of the facility. A Power to Heat solution was developed by installing a heat pump to use the heat from the on-site resin production facility (typical process temperatures range 120-180 °C) to pre-dry the OSB strands, before feeding them back into the original dryer. The resulting electrical power demand was brought to less than 30 kWh, and thermal consumption was brought below 1.05 MWh per ton of water. This innovative solution increased the plant capacity, adding an additional 13 tons of water evaporation capacity (Stela Drying Technology, 2023).

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## 10. UPM KORKEAKOSKI SAWMILL, FINLAND

**HEAT GRADE:** LOW, LOW-MEDIUM

**TECHNOLOGY:** HEAT PUMP

The UPM Korkeakoski sawmill has faced challenges of drying timber in the winter season. Atmospheric changes during winter can lead to bottlenecks forming in the drying kiln, leading to a reduced capacity (lower temperatures of material require longer heating periods to process the timber). Exploring Power to Heat solutions, an industrial heat pump with a 1MW thermal capacity, was installed (with room to expand up to 2MW in the future). The heat pump uses the waste heat from the drying kiln to reduce the amount of biomass burned. This upgrade has increased the sawmill's capacity during the cold winter periods, while also reducing electricity demand during periods of higher electricity cost (UPM Energy, 2022). The "Calefa AmbiHeat" heat pump system employed, can produce temperatures of over 100 °C. It collects outside heat and processes it to a much higher temperature so that it can be utilised efficiently. The AmbiHeat modular system allows for geothermal, solar, wastewater, and industrial heat to be used as the heat source for the industrial processes. The AmbiHeat systems are modular and scalable, from 360kW to 10MW in size, also allowing for remote monitoring and control (Calefa, 2025).

## 11. CARELLA, UK

**HEAT GRADE:** LOW

**TECHNOLOGY:** INFRARED

Carella, a Medium-Density Fibreboard (MDF), Plywood and chipboard manufacturing facility had encountered issues with bonding of melamine and Formica sheets (decorative cover layers used for furniture). Application of heat to the boards was necessary before the application of glue/bonding. This was inefficient through traditional means as the temperature, and risk of dust via fans led to boards being rejected due to poor bonding, dust contamination, and delamination of the decorative layers. Using an infrared heating solution, localised heating was provided to the processed boards, right before the bonding process took place. The upgraded system allowed for laminating of MDF, plywood and chipboards, reduced rejection rates of product and improved the overall quality of the product. The system was sized at 21kW, operating at 20% power draw at standby, with steps up to full thermal output. ('NobleLight', 2021)

### 3.11 Heat Use in the Other Minerals Industry

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Industry such as the processing of raw earth materials (clay for bricks and ceramics, stone aggregate and building material production, and glass manufacture) are classified under this section.

Within this industry, heat is mainly produced through the conventional methods of kilns and dryers fuelled by fossil fuels. Recently, biomass alternatives and electrical resistance heating is found in certain applications.

Heat is necessary for processes such as drying, firing, vitrification, calcination and raw material preparation. Heating facilitates moisture removal, chemical transformation, fusing of particulates, and property enhancements such as aesthetics, durability and strength.

The industry primarily needs high grade heat exceeding 800 °C and medium grade heat of 150-800 °C for drying processes.

### 3.12 Other Minerals Industry Case Studies

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#### 12. ARDAGH GLASS PACKAGING-EUROPE (AGP-EUROPE)

**HEAT GRADE:** HIGH

**TECHNOLOGY:** RESISTANCE HEATING

The Ardagh glass packaging site is advancing Power to Heat innovation in the Glass sector with its next generation furnace. This pioneering hybrid system uses direct electrical resistance heating via electrodes, aiming to achieve an 80% share of electrical heating alongside 20% gas. Since the beginning of 2024, glass bottles produced using this furnace have consistently delivered a 64% reduction in CO<sub>2</sub> emissions, saving approximately 18,000 tonnes of CO<sub>2</sub> marking a significant milestone in industrial decarbonisation (Ardaghgroup, 2024).

## 13. WIENERBERGER ÖSTERREICH GMBH PLANT, AUSTRIA

**HEAT GRADE:** LOW, HIGH

**TECHNOLOGY:** INFRARED HEATING, HEAT PUMPS

This brick factory has installed an industrial high temperature electric kiln for clay brick firing and three industrial high-temperature heat pumps for the clay brick drying process. These upgrades have been part of an effort to develop Power to Heat systems onsite. The electric kiln is approximately 90 metres long and designed to achieve brick firing temperatures of 800 – 1100 °C using infrared heating. For drying, the three heat pumps utilise recovered heat to provide temperatures of 100 – 200 °C range, enhancing the drying efficiency of the plant. The systems are powered by green electricity, sourced from an expanded on-site photovoltaic system, and supplemented by purchased hydropower. This revamp has resulted in a projected 90% reduction in CO<sub>2</sub> emissions, and 33% cut in the overall energy consumption of the plant. The result is an almost carbon-neutral brick production process (Wienerberger, 2024).

## 14. eLITHE PROJECT (VARIOUS PILOT SITES)

**HEAT GRADE:** HIGH

**TECHNOLOGY:** ELECTRIC RESISTANCE HEATING, INDUCTION HEATING, MICROWAVE HEATING

The eLITHE project is a collaborative initiative focusing on the electrification of high temperature thermal processes in the mineral industry to enable Power to Heat in the brick production and aluminium, ceramic and brick manufacturing industries. The project seeks to explicitly demonstrate three distinct electric heating technologies at relevant scales:

- The demonstration in Spain investigates electrification of a ceramic frit<sup>7</sup> smelter using resistive and induction heating technologies (up to 1500 °C). The project incorporates induction heating to maintain the product minerals in a liquid form, while the resistive heating technology will function as the main heating component.
- A demonstration in Greece uses a microwave-based Calcination furnace (Microwave heating at 1000 °C), utilising up to 70kW of power. The demonstration includes real time feedback, and automatic adjustments for accurate process control.
- The demonstration in Germany looks at retrofitting a Tunnel kiln with high temperature recirculation fans and hybrid burners (1100 °C). This brick firing kiln demonstration aims to adapt the current brick production process to maximise electrification while maintaining product quality, in addition to lowering emissions and costs.

The eLITHE project seeks to boost circularity across the minerals industry and create digital twins<sup>8</sup> for system optimisation and monitoring. While specific energy and emissions savings for the completed demonstrations are not yet available, the technical viability and scalability of the technologies are currently undergoing demonstrations. The project is expected to complete in 2027. The project will later integrate heat storage for improved energy management by using ceramic waste to store high-temperature heat (CIRCE, 2024).

<sup>7</sup> Frit is a mineral composition used in the smelting of glass.

<sup>8</sup> Digital Twins are simulated replicas of a plant or process, used to optimise the real-world processes.

### 3.13 Heat Use in the Food and Drink Industry

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The Irish food and drink industry comprises diverse processes, including dairy, meat and seafood production, brewing and distilling, UHT treatment/sterilisation, confectionery and prepared foods. Process heat is necessary in most of these manufacturing processes. Typically generated by steam boilers (natural gas or biomass), direct-fire ovens and

furnaces, hot water systems and more recently, heat pumps and electric heating systems. Medium grade heat is essential for the core processes of pasteurisation, sterilisation, cooking (e.g. baking and frying), evaporating, cleaning-in-place and distillation (150 – 350°C). Low-grade heat is required for drying and boiling (<150°C).

### 3.14 Food and Drink Industry Case Studies

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#### 15. HEINEKEN BREWERY, MANCHESTER, UK

**HEAT GRADE:** LOW, MEDIUM

**TECHNOLOGY:** HEAT PUMPS

To reduce emissions, the Heineken brewery has adopted a Power to Heat approach by integrating a heat pump system into its existing facility. The low-carbon solution of an electric heat pump network delivers hot water at 90 °C throughout the brewery, replacing the legacy steam boilers with an environmentally friendly alternative. The heat pump supplies heat across multiple stages of the brewing process. This upgrade has led to a 45% reduction in gas consumption in the brewery (GEA, 2023).

#### 16. HEINEKEN BREWERY, ZOETERWOUDE, NETHERLANDS

**HEAT GRADE:** LOW, MEDIUM

**TECHNOLOGY:** HEAT PUMPS, RESISTANCE HEATING

Collaborating with Eneco, the largest brewery in Europe, Heineken undertook the challenge of switching to a fully electrified process with a two-year deadline. The project began with an aim to maximise on-site green energy generation and insulate the hot and cold pipelines to minimise heat loss. The next stage involved installing two 4 MW heat pumps, and a 12 MW resistance heating e-boiler, running on renewable energy. The e-boilers are capable of rapidly heating water, generating steam for pasteurisation, and sterilising packaging, while working at a high efficiency. Should a water storage system be added, excess renewable energy can be stored in the form of heated water. Heineken intends to for its entire value chain to be CO<sub>2</sub>-neutral by 2040 (Eneco, 2018).

## 17. PARTNERS IN PET FOOD (PPF), DOMBOVAR, HUNGARY

**HEAT GRADE:** MEDIUM, HIGH

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

The largest pet food producer in Europe is decarbonising some of its factory operations using a thermal heat storage solution at its pet food manufacturing facility in Hungary. Collaborating with Brenmiller Energy, a 30MWh sensible heat battery uses crushed rocks to store heat (up to 650 °C) (EnergyTech, 2024). The heat is generated from renewable electricity or low-cost grid power. The system can supply decarbonised heat, steam, or hot air for continuous operations, and the intention is to replace the manufacturing facility's fossil fuel boilers. The project is estimated to cost \$5 million US dollars. The heat storage system is owned by the Brenmiller Energy company, with PPF buying steam at a fixed rate, lowering both operational costs and carbon emissions (Bren-energy, no date).

## 18. FRIESLAND CAMPINA, MAJOR DAIRY COOPERATIVE

**HEAT GRADE:** LOW, MEDIUM

**TECHNOLOGY:** HEAT PUMPS

Friesland Campina, a major dairy cooperative has worked with the European Heat Pump Association (EHPA) to promote and boost the uptake of industrial Power to Heat solutions, such as heat pumps, in the milk processing industry. The cooperative undertook a project to transfer the production of their facility to renewable electricity, without increasing emissions. Implementing a combination of conventional heat pumps and innovative steam pumps, the project was able to demonstrate that previously expelled waste heat had the ability to supply the facilities production processes, including pasteurisation. This resulted in a 36% reduction in energy consumption and emissions. The heat pumps the facility used achieved temperatures of up to 150 °C, making it ideal for industrial applications. Alternative models from the same heat pump manufacturer, employing a Brayton-cycle-based system, can reach temperatures of 230 °C while simultaneously providing cooling as low as -30 °C (EHPA, 2024).

## 19. TEMPO BEVERAGES LTD., NETANYA, ISRAEL

**HEAT GRADE:** LOW, LOW-MEDIUM

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

'Tempo' is one of Israel's largest beverage producers and distributors. It has recently begun an upgrade of its beverage plant via the instalment of a combined Power to Heat system and a heat storage system. A 32 MWh sensible heat battery system will replace the beverage manufacturer's existing heavy fuel oil boilers. The thermal energy storage uses the Brenmiller crushed rock heat storage method, capable of storing heat for days, with a reported 0.1% heat loss rate per hour. With this upgrade, the facility is estimated to eliminate the need for approximately 2000 tons of heavy fuel oil and mitigate 6200 tons of CO<sub>2</sub> emissions on an annual basis. This will translate to estimated energy cost savings reaching \$7.5 million over a 15 year period (Businesswire, 2023).

## 20. VEGETABLE OIL PRODUCER, UNKNOWN

**HEAT GRADE:** LOW

**TECHNOLOGY:** MICROWAVE

A company in the food and drink industry successfully adopted microwave-based technology to extract high-quality vegetable oil from leftover fruit pits, a common by-product of juice production. Traditionally, the high moisture content in these pits made oil extraction inefficient, and conventional heating methods risked damaging the oils by exceeding safe temperatures.

Using a 76 kW microwave system, the company was able to process up to 5 tonnes of raw material per hour, gently removing moisture at temperatures up to 70 °C. This precise, low-temperature heating preserved the quality of the oils while preparing the pits for efficient extraction. The case demonstrates how microwave P2H solutions can transform food processing by improving resource efficiency, reducing waste, and adding value to by-products (MEAM International, 2022).

### 3.15 Heat Use in the Lime Industry

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The lime industry is dedicated to the production of quicklime (CaO) and hydrated lime (Ca(OH)<sub>2</sub>), materials necessary for construction, agriculture, environmental applications and industrial processes. Heat is produced through combustion of traditional fossil fuels in rotary kilns and shaft kilns. The heat is essential for the calcination

process and the associated drying processes in hydrated lime production. Heat enables the decarbonation process to take place, converting limestone into quicklime and removing moisture.

The industry requires temperatures exceeding 900°C for the calcination processes.

### 3.16 Lime Industry Case Studies

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#### 21. SMA MINERALS AND SALTX TECHNOLOGY – ZERO EMISSION QUICKLIME

**HEAT GRADE:** HIGH

**TECHNOLOGY:** PLASMA HEATING

A partnership between SMA Minerals and SaltX is set to open a demonstration plant in 2025. The plant seeks to produce zero emission quicklime using Power to Heat manufacturing methods and a brand-new factory concept, designed from the ground up. The company seeks to revolutionise the calcination process with an innovative Plasma heat based Electric Arc Calciner (EAC) furnace. The EAC furnace will generate plasma from renewable electricity and capture the CO<sub>2</sub> emissions during the heating process. Granular details, however, are not available (SaltX Technology, 2025).

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## 22. LEILAC-1, DEMONSTRATION PLANT, LIXHE, BELGIUM

**HEAT GRADE:** HIGH

**TECHNOLOGY:** PLASMA HEATING

Due to the high process CO<sub>2</sub> emissions in the lime industry, novel technologies are needed to both enable Power to Heat technologies in high grade heat industries, and capture process emissions. This pilot plant in Lixhe, Belgium was developed as part of the EU Horizon 2020 programme, built as a proof of concept for the Leilac decarbonisation technology. The technology can be heated using both electric and conventional energy methods. The technology provides direct separation of CO<sub>2</sub> process emissions, offering a pathway for emissions containment (such as underground storage). The technology has proven to have no negative impacts on the host plant, the production, nor does it have any additional energy demands compared to conventional plants (The Leilac, 2023).

### 3.17 Heat Use in the Chemical Industry

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The chemical industry spans a diverse range of products and processes. Pharmaceuticals, chemicals, polymers, fertilisers, industrial gases are all essential products which demand the need for substantial amounts of energy in their manufacture. Heat is primarily generated by fired heaters, industrial steam boilers and electric heating technologies like heat pumps and resistance heaters. These heating methods are necessary to enable processes like distillation, evaporation, drying, chemical reaction heating,

polymerisation and sterilisation. Heat enables chemical reactions, phase changes, separation and purification, removal of solvents or moisture from products, and precise temperature control for efficiency and product quality.

The chemical industry utilises all heat grades, from sub 150 °C temperatures for heating hot water, to 150 – 500 °C for distillation and drying, to over 500 °C for processes such as pyrolysis, cracking or steam reforming.

### 3.18 Chemical Industry Case Studies

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#### 23. AVERY DENNISON PERFORMANCE TAPES, TURNHOUT, BELGIUM

**HEAT GRADE:** MEDIUM

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

This packaging manufacturer has commissioned Europe's largest Concentrated Solar Thermal (CST) platform and a sensible heat storage unit at its production plant. Once operational, the CST will provide a peak solar yield of 2.7 GWh of thermal power and six thermal storage modules, totalling 5 MWh of thermal power. The installed system will provide heat equivalent to 2.3 GWh of gas consumption, reducing the plant's annual emissions by 9% annually, and eliminating 100% of the factory's heat demand during the summer months. Once the CST and the heat storage are coupled, high-temperature thermal energy can be dispatched both day and night, on demand. The project will provide heat to run drying ovens used in the coating process of pressure-sensitive adhesive products (EnergyNest, 2023).

## 24. YARA PORSGRUNN, NORWAY

**HEAT GRADE:** LOW, MEDIUM

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

This chemical plant implemented a thermal energy storage solution, led by Energynest. The heat storage system is implicitly charged with excess heat from YARA's various energy-intensive chemical processes, via industrial boilers. The sensible heat battery stores a high-pressure steam (34 barg), later to be released as a low-pressure dry steam at 5 barg and a flow rate of 1-5 tons per hour. The steam can be used to balance the steam grid within the plant, reduce reliance on boiler operation, or in a steam turbine for power generation (EnergyNest, 2020).

## 25. CALGREN RENEWABLE FUELS, USA

**HEAT GRADE:** HIGH

**TECHNOLOGY:** RESISTANCE HEATING, SENSIBLE HEAT STORAGE

Calgren is a biofuel producer, manufacturing ethanol, biodiesel, and Renewable Natural Gas (RNG) from agricultural and waste feedstocks. Calgren claims to produce the world's lowest carbon intensity ethanol, biodiesel and RNG, at their Pixley facility in California. The Pixley facility employs an electric sensible heat energy storage system, the Rondo Heat Battery, which comprises an integrated Power to Heat and heat storage system.

The Rondo Heat Battery (Rondo Energy, 2025) acts as an "industrial thermal battery." It uses resistance heating to convert intermittent, low-cost renewable electricity into very high-temperature heat, storing it efficiently in a massive, insulated stack of refractory bricks. This stored heat can then be delivered as continuous, high-temperature process heat (hot air or steam) to industrial facilities. It effectively replaces fossil fuel combustion for applications like preheating, drying, or even some calcination processes. The technology is designed to decouple the electricity input from the heat demand, allowing industries to purchase electricity when it's cheapest (e.g., during off-peak hours or when renewable generation is high) and use the heat continuously 24/7 (Biodiesel Magazine, 2023).

## 26. STICKY TAPE MANUFACTURER, UNKNOWN

**HEAT GRADE:** LOW

**TECHNOLOGY:** MICROWAVE

A sticky tape manufacturer faced drying inefficiencies due to the presence of bound water in the water-based adhesive applied to a paper base. Conventional heating methods slowed down significantly toward the end of the drying process. To address this, a custom-designed 8 kW microwave system was deployed, which enabled direct molecular excitation of water, even when bound, maintaining a constant and efficient drying rate at temperatures up to 70°C. The solution was seamlessly integrated into the existing production line, achieving a throughput of 20 metres per minute and significantly improving process speed and energy efficiency (*MEAM International*, 2022).

### 3.19 Heat Use in Other Industry

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Heat use in other industries encompasses a diverse array of industrial activities that do not fit neatly into the other sectors, but whose heat demand must still be considered. This broad category would include operations within the textile, engineering, packaging and electronics industries and other miscellaneous processes.

Within these industries, heat would primarily be generated through

conventional technologies such as industrial boilers and heaters. Heat is essential for enabling processes such as treatment, cleaning, drying, curing and mixing.

This diverse industrial sector would predominantly utilise Medium-Low grade heat (100°C-200°C) and Low-grade heat (<100°C) for diverse processes including climate control in large spaces or heating certain components within manufacturing processes.

### 3.20 Other Industry Case Studies

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#### 27. INSULATION MATERIALS MANUFACTURER, UNKNOWN

**HEAT GRADE:** LOW

**TECHNOLOGY:** MICROWAVE

A manufacturer of insulation materials for ovens faced high energy costs due to inefficiencies in its coating drying process. The production involved applying a powdery white coating to rope-like insulation material. With conventional heating, both the coating and the underlying rope were heated, even though only the coating needed drying. This led to unnecessary energy use and thermal stress on the material. A tailored 9 kW microwave P2H system allowed the company to heat only the coating material, dramatically reducing unnecessary energy use. The system operated at 120 °C and achieved a throughput of 140 metres per minute (*MEAM International*, 2022).

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## 28. PURIFICATION PRODUCTS, UK

**HEAT GRADE:** LOW

**TECHNOLOGY:** INFRARED

Purification Products, a manufacturer of filtration materials for industrial and medical use, sought to improve the drying process for a new filter medium using a water-based latex binder. Although the company already used infrared (IR) drying technology, the existing setup was no longer sufficient to meet rising production demands, with drying times reaching up to 30 minutes. In collaboration with Heraeus Noblelight, a 27 kW medium-wave IR booster system with three independent heat zones was added to the line. The upgrade significantly reduced drying times, improved energy efficiency, and enhanced product quality ('Heraeus Noblelight', 2020).

## 29. AIRBAG MANUFACTURER, UK

**HEAT GRADE:** LOW

**TECHNOLOGY:** MICROWAVE

A company that manufactures airbags faced challenges in recycling polyamide powder scraps. The company needed to dry the powder, which is a sensitive material that becomes explosive when dry and discolours if heated above 70°C. The moisture needs to be lowered from 20% to 0.5% moisture content. This creates a challenge of drying the powder gently and safely. The conventional drying solutions like fluidized beds, steam, or infrared heaters were inefficient and unsafe in an ATEX environment. These methods struggled to dry the powder uniformly and risked exceeding the critical temperature, leading to product rejection and safety concerns. To overcome these issues, the company implemented a high-frequency microwave dryer. The new system, which delivers a power of 120 kW, can evaporate up to 120 kg of water per hour. This technology uses volumetric heating to dry the product from the inside out, selectively heating the water molecules without raising the polyamide powder itself above the 70°C limit. This approach resulted in a quick, gentle, and uniform drying process, ensuring safety and product quality (*iSpecc*, no date).

## 30. LEONHARD KURZ, SULZBACH-ROSENBERG, GERMANY

**HEAT GRADE:** LOW, LOW-MEDIUM

**TECHNOLOGY:** SENSIBLE HEAT STORAGE

Leonhard Kurz is an industrial thin film and speciality manufacturer, specialising in the production of decorative and functional film layers for printing, packaging, plastics, automotive, electronics and medical applications. The company has implemented an Energynest thermal energy storage system in its plant to enhance operational flexibility (such as heat availability at night, during high demand periods) and to optimise the industrial process heat. The installed battery enables KURZ to utilise excess solar energy from the onsite PV. The installed system provides sensible heat storage for 3 GWth of clean heat annually, covering over 70% of the heat demand for one of the sites production lines. Over 40% of the heat demand will be met directly from the stored heat. This will reduce the natural gas consumption by 3.5 GWh, and cut CO2 emissions by 700 tons, per year (EnergyNest, 2025).

## 31. CALDERA FACTORY DEMONSTRATION, FAREHAM, UK

**HEAT GRADE:** MEDIUM

**TECHNOLOGY:** RESISTANCE HEATING, SENSIBLE HEAT STORAGE

At Caldera's facility in Hampshire, an on-site thermal battery system showcases how industrial heat can be decarbonized. The factory has operated a 100 kWh prototype thermal heat storage cell for five years, providing heat and hot water to their offices. This prototype stores surplus power (e.g. from solar) as heat at ~400 °C in a vacuum-insulated steel cylinder filled with aluminum-basalt composite. Water is later injected to produce steam on demand for heating. Building on this success, Caldera constructed a full-scale 4 MWh storage boiler. The industrial system can boil a 15,000 L water tank in under an hour, delivering pressurized steam up to ~200 °C for manufacturing processes. It is designed as a drop-in replacement for gas-fired boilers, enabling factories to use cheap renewable electricity for steam generation (Caldera, 2025).

The Caldera Heat Battery is an electric-thermal storage unit that charges using electricity, either from the grid or on-site renewables, and stores heat in vacuum-insulated blocks. When steam or hot water is needed, the stored heat is released through a compact heat-exchanger to feed industrial processes. A built-in control system manages charging and discharging, letting factories run high-grade heat applications flexibly and on clean power.

# Section 4: Enabling Power to Heat in Ireland?

With growing pressure on business to reduce the impact of industrial heating processes, the decarbonisation of heat will depend on the adoption and retrofitting of new heating processes and technologies. Documents such as this guide intend to provide industry with an overview of available technologies, options, common practices and recommendations to support the electrification of heat in industrial processes. Electrification is pivotal to decarbonising industrial heat, especially when paired with renewable electricity production.

This section will outline some of the key takeaways from the investigated case studies, as well as the wider literature discussed throughout the document, it will highlight the barriers to the widespread deployment of power to heat and heat storage technologies, and offer recommendations.

## 4.1 Key insights from case studies and wider literature

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Electrification technologies for industrial heat are technically viable, increasingly commercially available, and steadily evolving. Case studies and wider literature show that industrial heating demands, particularly those below 500°C, can already be met by existing electrified technologies. Heat pumps, electric arc furnaces, and resistance heaters are proving capable substitutes for fossil-fuel-based systems, especially in low- and medium-temperature applications. In parallel, thermal energy storage offers a promising means of improving flexibility and aligning industrial heat demand with renewable energy supply. Across multiple sectors, real-world examples demonstrate significant energy and emissions savings from the switch to electrified heating. However, deployment remains uneven. High-temperature processes continue to face technical and commercial barriers, some newer technologies still require demonstration, and the widespread integration of heat storage is limited. Insights found a broader issue: even where solutions are available, adoption is slow due to practical, economic, and organisational challenges, highlighting that the central challenge is no longer technology development, but deployment at scale.

## **Industrial electrification technologies are mature, available, and still evolving**

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The commercialization status of different industrial electrification technologies varies widely, but all industrial heating needs can technically be met by at least one existing electrified technology, if not more. While many Power-to-Heat technologies are approaching or have recently reached commercial readiness, further progress is needed in their adoption and in establishing them as the new standard in industrial heating solutions.

Despite high-grade heat processes remaining the most difficult to electrify, certain high-temperature electrical heating technologies are also commercially available, such as electric arc furnaces for steelmaking, and lasers or plasma torches for cutting and welding. However, in other cases, technologies for electrifying high-temperature heat still require further development and commercialisation before they are ready for large-scale industrial use. For example, while electrical resistance heating is a mature technology, it is not readily available across all industrial applications. Many specialised machines (such as kilns, dryers, or reactors) are still only offered in fossil-fuel-heated versions, and electrically heated models are either unavailable or not yet commercialised. In these cases, the challenge lies not in the Technological Readiness Level (TRL) of the heating technology itself, but in the lack of commercially available equipment designed to integrate with specific industrial needs.

## **Deployment, not development, is the challenge for proven electrification technologies**

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Most industrial process heat under 500°C can be electrified with commercially available technologies. However, industrial firms' lack of familiarity with these technologies impedes their adoption.

Some technologies are fully commercialized but have not yet reached their full deployment potential, such as induction furnaces for metals manufacturing and electric arc furnaces for steelmaking because their integration often requires substantial process changes, high upfront capital investment, and reliable access to affordable, high-capacity electricity.

Amongst available electrification options, industrial heat pumps stand out as the most promising replacement for low-temperature industrial boilers (operating up to approximately 165–200°C, the upper limit for most heat pumps). Although these heat pumps are commercially developed, their broader deployment is hindered by several practical challenges. Global manufacturing capacity, particularly for units that can achieve temperatures above 120°C, remains constrained.

## **New technologies are still emerging, but further development and demonstration are needed**

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While several alternative technologies, such as dielectric heating, infrared, and ultraviolet heating, are commercially available and already used in industrial applications, they remain limited to niche roles and contribute only a small

fraction to overall industrial energy consumption.

Case studies indicate that technologies as microwave or infrared heating are not commonly employed as a mainstream substitute for conventional fossil-fuel heating systems. Instead, both technologies are typically used in specific scenarios where traditional methods fall short. Their effectiveness in niche processes makes them valuable tools in certain industries; however, limitations related to energy distribution, penetration depth, and the need for customised system design constrain their wider adoption for general heat electrification.

Other technologies, as plasma torches for cement production, for example, would benefit from more real-world pilots and demonstrations to improve performance, reduce costs, and scale adoption.

### **Heat storage remains underutilised in Power-to-Heat strategies despite clear benefits**

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Despite its relevance for improving flexibility and making better use of renewable energy, heat storage is rarely integrated into Power-to-Heat projects. Where industrial heat storage applications are identified, they are most often coupled with renewable energy generation (e.g. Concentrated Solar Power (CSP) plants).

Examples of heat storage applications found within investigated case studies and wider literature, primarily rely on sensible heat technologies, using dense materials like crushed rock and thermal bricks to store heat. The technology can be integrated into existing industrial processes with minimal disruption. Its

main appeal lies in reducing heat demand during peak hours, avoiding high tariffs, and improving the energy efficiency of the existing processes.

### **Electrification is already visible in low- to medium-temperature industrial processes**

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From what the case studies show, industries with low to medium heat demands, such as Food and Drink, Chemicals, and Wood Products, are well suited for electrification using commercially available technologies. Heat pumps and electric resistance heating are particularly effective in applications involving hot water, boiling, or steam generation. In the Food and Drink sector, batch processes and cyclical thermal loads create favourable conditions for pairing electrification with thermal energy storage. Similarly, in the Wood Products sector, processes like drying and pressing can be decarbonised using electric boilers or resistance heaters, with thermal storage offering further flexibility.

### **Thermal energy storage enhances flexibility, especially in batch and modular processes**

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Case studies suggest that Thermal Energy Storage (TES) can play a key enabling role in electrifying industrial heat when demand is cyclical or predictable. In sectors such as Food and Drink or Chemicals, TES systems allow firms to shift electricity consumption to off-peak periods, better align with on-site renewable generation, and improve system efficiency. While TES technologies like hot water tanks or ceramic bricks are mature, their

integration remains most effective when tied to specific operational patterns, such as batch processing or modular lines. TES is particularly valuable when deployed alongside Power-to-Heat solutions in contexts where continuous heat is not required.

### **Electrification of high-temperature processes remains more complex and case-dependent**

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Electrification of high-temperature processes, such as those found in Metals and Engineering, is more challenging due to the energy intensity, material characteristics, and integration requirements. While technologies like electric arc furnaces and induction heating are commercially available, their application is limited by factors such as part size, process precision, and grid capacity. Some lower-intensity processes in these sectors (e.g. heat treatment or tempering) appear more feasible for electrification in the near

term, especially when paired with targeted upgrades to electrical infrastructure and process controls.

### **Electrification of industrial heat is progressing in Ireland, but still lagging behind other countries**

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Case studies and publications on Power to Heat projects are less common in Ireland compared to other European countries. This reflects a more limited number of large-scale industrial deployments to date, as well as lower visibility of pilot projects. In contrast, countries like Germany, the Netherlands, and Denmark have more pilot and commercial-scale installations, as well as stronger public-private coordination mechanisms to help document and disseminate project outcomes. These are expected to be decisive factors in boosting wider adoption of these technologies.

## 4.2 Key Barriers to the Implementation of P2H Technologies and Heat Storage Solutions

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The deployment of power to heat and heat storage in Ireland still faces a range of barriers. These include high electricity prices relative to fossil fuels, grid capacity constraints, and the complexity of integrating new systems into existing industrial infrastructure. Organisational risk aversion, long equipment lifetimes, and limited awareness or in-house expertise further slow adoption. Overcoming these challenges is essential to unlock the full potential of electrified heat and storage solutions in industry.

### The Differential Between Fossil Fuel and Electricity Rates

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#### POWER TO HEAT

High operational costs due to electricity prices, especially compared to fossil fuels, consistently comes up as the most cross-cutting, immediate obstacle to deployment of power to heat solutions in industry, across sectors and geographies.

In most regions, electricity is several times more expensive per unit of energy versus fossil fuels, even after accounting for taxes and subsidies. This means that an electric heating technology often must outperform its fossil fuel counterpart several times over (in efficiency, precision, or speed) to overcome this price gap. However, that level of performance is not always guaranteed across all Power-to-Heat technologies and applications.

### Integration with Existing Infrastructure and Operations

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#### POWER TO HEAT | HEAT STORAGE

Replacing conventional fossil fuel-fired heating systems with alternative ones – such as electricity powered systems or those using stored heat – may require industrial facilities to significantly modify

their existing electrical and thermal infrastructure. In this sense, the more integrated a facility's systems are, the more difficult it becomes to electrify heating demand using simple drop-in technologies.

In addition to investing in new heating equipment, facilities may also need to expand their electrical infrastructure onsite, offsite, or both. This can include upgrading transformers, switchgear, electrical panels, and wiring to handle increased electricity demand, besides requiring a higher Minimum Import Capacity agreed with the utility. Coordination with the local utility may be necessary to carry out these upgrades.

Integration challenges also apply to TES. Ensuring compatibility and seamless operation is critical to achieve the desired energy efficiency and sustainability outcomes. Although technologies like water tanks or PCMs are well-established and can deliver heat effectively in industrial settings, their integration is not always straightforward. Matching the stored heat to the specific temperature, timing, and operational needs of a process often introduces complexity, requiring the need to overcome engineering challenges. Besides these issues, adapting existing systems to

accommodate storage can add additional costs.

To get the full benefits of TES, systems also need advanced controls to manage charging and discharging cycles and to respond to changes in grid demand. If TES is meant to be charged using directly renewable electricity, delays in expanding renewable generation or upgrading the grid can hold back its deployment.

## Grid Readiness

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### POWER TO HEAT | HEAT STORAGE

Grid readiness is a key technical barrier. Low-carbon electricity production is a persisting issue against the backdrop of increasing electricity demand from growing industries, and the emergence of data centres. At a foundational level, the existing Irish grid is underdeveloped. Dispatch-down is a prevailing issue on the island, with some regions such as the north-west experiencing nearly 20% dispatch-down on generated renewable energy sources. Significant development is required to modernise the current electrical grid to support the electrification of existing industries in Ireland. This includes the transmission and distribution grids. These upgrades are expensive and require significant lead times due to the complexity of balancing the grid.

On the companies' side, grid connection upgrades are capital intensive, and long-term utilization certainty is needed to justify investment. In addition, approval timelines for grid upgrades may not align with business investment cycles.

## Organisational and Investment Barriers

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### POWER TO HEAT | HEAT STORAGE

Asset turnover rates is another key barrier to rapid technology shift. Industrial equipment often has a long lifetime and, especially for capital intensive equipment, the economic case for replacing working fossil-fuelled equipment is weak without strong policy incentives (Berkeley et al., 2024)

Furthermore, industrial facilities are typically risk-averse, and replacing long-standing, familiar heating systems with new technologies may introduce several operational and organisational challenges and increase risk. These include potential process disruption, uncertainty around performance, the long-term reliability and maintenance requirements of new technologies, the need for staff retraining, and resistance to change within the organisation.

## Lack of awareness and technical expertise

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### POWER TO HEAT | HEAT STORAGE

Another challenge is the need for skilled personnel to install, operate, and maintain power to heat technologies and TES. Like the shortage of skilled personnel in the renewables sector, technical expertise in heat storage fabrication is lacking in Ireland. This skillset is more abundantly found in mainland Europe. Ireland needs to undertake significant workforce development to ensure it can keep up with industry demands for renewable technologies, through means like Skillnet Ireland, which seeks to build competitiveness through skills development.

From an industry perspective, limited awareness of the operational and cost-saving benefits of both Power-to-Heat and TES technologies contributes to a lack of momentum for change. This is especially true among small and medium-sized enterprises, where internal energy expertise may be limited. The transition from fossil-based heating systems to electrified alternatives is critical for industrial decarbonisation, but without clear understanding of technology options, performance expectations, and integration pathways, many firms remain hesitant to act. Building awareness and technical capacity will be essential to foster wider adoption, through training programmes, demonstration projects, and advisory support.

## Technical Limitations and Trade-Offs of Heat Storage Types

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### HEAT STORAGE

Even though sensible heat storage materials, like water or rocks, support higher operating temperatures and allow for simpler system design, they have relatively low energy densities, requiring large storage volumes and footprints that can be impractical for some industrial locations.

On the other hand, latent heat storage solutions (or PCMs) offer higher energy density, but operate within narrow temperature ranges. Some PCMs, particularly salt hydrates, may degrade over time due to phase separation or supercooling, which reduces thermal storage capacity and lifespan. Additionally, many PCMs have low thermal conductivity, which slows

charging and discharging. Solutions such as encapsulation can improve stability and thermal performance, but they add to the overall system cost.

Thermochemical TES is a technology that offers high energy density, addressing some of the limitations of other thermal storage methods. However, its technological readiness level is still relatively low and requires further development. Among the key challenges is the need for materials that can withstand high temperatures, pressures, and repeated thermal cycling without degradation, posing significant material science and engineering difficulties.

## High initial investments and Low Return on Investments Hinder the Deployment of TES

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### HEAT STORAGE

One of the major barriers to the widespread adoption of TES is the high upfront investment cost. While these systems can deliver long-term benefits in terms of energy savings, flexibility, security and emissions reduction, the initial capital expenditure can be difficult to justify for many industries, particularly those requiring short payback periods. The economic case is further challenged by the fact that TES systems often need to be tailored to specific processes or integrated into existing infrastructure, adding to complexity and cost (*NenPower*, no date). Supportive policies along with financial incentives, such as grants, low-interest loans, or tax credits, are therefore essential to reduce investment risk and support broader deployment (Ma *et al.*, 2025)

## 4.3 Boosting the deployment of P2H and Storage solutions in Ireland

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Industrial electrification of heat and the adoption of thermal energy storage require a coordinated, systemic effort across multiple fronts.

A reliable and flexible electricity grid is essential to accommodate the increased loads and enable integration of heat systems with variable renewable generation. Access to suitable finance, through grants, low-cost loans, and co-investment models, is needed to overcome high upfront costs and narrow return margins that characterise many industrial heat projects. Industry engagement is equally important: businesses must be aware of available solutions, understand their technical and economic potential, and be supported in developing robust decarbonisation strategies. Workforce skills must evolve in parallel, ensuring operators and engineers can safely install, operate, and maintain new electrified systems and digital controls.

Policy has a pivotal role to unlock and align all these enablers: grid infrastructure, finance, business engagement, and skills. It can clear the way by setting the direction, reducing uncertainty, and creating the conditions for widespread adoption of electrified heat and storage solutions across industry.

### Laying the Groundwork for Electrified Heat

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In Ireland, several concrete steps to support the deployment of P2H and TES in industry have already been taken.

To begin with, Ireland's Department of Enterprise published a Roadmap for the Decarbonisation of Industrial Heat in 2024. The document outlines key policy measures, regulatory updates, guidelines for electrification and thermal storage, and support schemes intended to help industry achieve the national target of a 35% emissions reduction by 2030 (*DETE, 2024*). This is particularly important as it provides clarity on upcoming changes affecting heat supply, sends a long-term signal to invest in electrified heat and storage solutions, and begins to address persistent deployment barriers, such as uncertainty, limited financial visibility, and integration with existing energy systems.

Additionally, the Irish government is planning to enhance financial supports through Enterprise Ireland and the SEAI, with targeted capital grants and green transition funding aimed specifically at decarbonising heat. A portion of the €300 million fund for low-carbon industry, announced in 2024, is earmarked for projects involving electrified heat and storage solutions. These financial tools are intended to ease the burden of high upfront capital costs and help overcome internal organisational resistance, especially in facilities with long-lived, depreciated fossil fuel equipment where replacement is not easily justified (*Enterprise, 2024*). At the moment, there is already a range of grants available from Enterprise Ireland, the IDA, SEAI and Údarás na Gaeltachta. The initial GreenStart and GreenPlus schemes can assist client companies develop a decarbonisation strategy, implement an environmental management system

and train staff. Capital grants for the implementation of significant decarbonisation projects are also available, with grant levels of up to €1m from the National Enterprise Hub (NEH, 2024) for qualifying projects and up to €3m through the SEAI Exceed Scheme for large industry projects (SEAI-EXEED, 2024).

Efforts are also underway to address the challenges related to grid readiness. ESB Networks is upgrading the grid to support renewables and electrified heat, while EirGrid is reinforcing the transmission system to handle growing demand and higher renewable penetration. Additionally, ESB Networks published their 2025–2029 Flexibility Plan, which includes pilot procurement of flexible electric heating and storage (eHeat) and offers flexible grid connection options for large energy users. A complementary Demand Flexibility Product is being developed offering industry the opportunity to shift or adjust loads in exchange for grid support payments. This enables heat processes and TES to act as controllable loads, improving grid stability while generating revenue. This programme, now moving beyond the pilot phase, has the potential to significantly improve the business case for industrial electrification, especially for facilities that operate flexibly or have thermal storage capacity (ESB, 2024). It complements the planned expansion of flexible connection contracts, which will give large energy users improved access to the grid based on operational profiles.

Another key development is the implementation of the Private Wires Policy, introduced by the government in mid-2025, which will enable direct, private electricity connections between renewable energy sources and industrial

sites (Department of Climate, Energy and the Environment, 2025). This measure, as set out in the Roadmap aforementioned, is expected to support industry investment in RES, reduce reliance on the public grid and, where feasible, lower the delivered cost of electricity. By doing so, it helps address the operational cost gap of electricity powered systems that often discourages electrification while tackling a major integration barrier by offering companies more control over energy sourcing and use.

On the knowledge and technical capacity side, SEAI is expected to expand its guidance materials and sector-specific tools, building on the 2025 release of the Electrification of Industrial Heat Guide (SEAI, 2025b). These resources are intended to support industries with low internal capacity, helping them understand the available technologies, evaluate feasibility, and manage integration with existing systems. In doing so, they aim to reduce the perception of technical risk and provide a clearer pathway to adoption.

Finally, Ireland applies a carbon tax, currently set at €56 per tonne of CO<sub>2</sub> (as of 2025) (Carbon tax, 2025), and expected to rise to €100 by 2030 (OECD, 2021). This price signal strengthens the relative competitiveness of electrified heat systems by increasing the cost of fossil fuel use, particularly relevant for heat-intensive industries. In parallel, the EU Emissions Trading Scheme (ETS), applicable to high-emitting sectors, and Ireland's carbon tax provide complementary mechanisms that assign a cost to emissions, incentivising industrial decarbonisation.

## Next Steps for Scaling Impact

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Despite recent progress, several key barriers to the industrial deployment of P2H and TES in Ireland remain. The most immediate and crosscutting is the high cost of electricity relative to fossil fuels, particularly in high-consumption sectors. Unlike countries such as Germany or the Netherlands, Ireland has yet to implement significant tax or levy reforms, exemptions, or preferential tariffs to address this cost differential and improve the running cost competitiveness of electrified heat.

In terms of governance, Ireland has not yet established a formal Industrial Electrification Alliance that brings together policymakers, industrial stakeholders, utilities, and the research and innovation community. While some national initiatives and consultation processes exist (mainly led by SEAI, Enterprise Ireland, and the Department of the Environment) there is no dedicated, structured alliance focused specifically on industrial heat electrification. This contrasts with other European countries, such as Germany, where an alliance of industry associations has united under a formal coalition calling for a coordinated decarbonisation strategy and dedicated process-heat electrification roadmap for industrial users. In Ireland, collaboration remains fragmented and mostly project-based, lacking a centralised platform for ongoing coordination, target-setting, and knowledge exchange.

On the financial side, Ireland currently does not operate a dedicated scrappage programme or emissions-based capital expenditure rebate scheme for industrial heating equipment. Existing financial supports, provide valuable investment support but are not explicitly

designed to incentivise the early replacement of fossil-fuel-based heating systems with low-emission alternatives. Nor are they performance-based in a way that scales support according to the environmental benefits achieved. In particular, there are no mechanisms in place to offer higher financial incentives where electrified heating solutions replace fossil-fuel equipment ahead of its expected end of life, or to promote the recycling or responsible disposal of old equipment, measures that are increasingly used in other jurisdictions, such as France and Germany, to accelerate clean technology uptake.

From a regulatory and standards perspective, Ireland has not yet introduced mandatory minimum energy performance standards for industrial heating equipment. While eligibility for some public funding may require meeting certain efficiency thresholds, such as Seasonal Performance Factors for heat pumps, these are not requirements for market access, as is the case in Germany, where the Ecodesign framework and national regulations enforce minimum efficiency levels for boilers and heat pumps before they can be sold. Without such mandatory standards, inefficient or high-emission equipment can continue to be sold and installed, delaying the market shift toward clean, high-performance alternatives. Moreover, there is no established timeline in Ireland for tightening such standards over time, which would otherwise help drive continual innovation and emissions reductions across industrial heating technologies.

When it comes to education and technical assistance, Ireland lacks a dedicated, regionally organised support structure to guide industrial firms

through the electrification of heat. While SEAI and other national bodies publish technical guidelines and provide general advisory support, this assistance is not tailored regionally or delivered through embedded technical advisers familiar with local industrial clusters. There are no localised centres or programs providing hands-on help to manufacturers evaluating electrified heating options, nor are there sector-specific training schemes that target the upskilling of plant engineers and energy managers in industrial electrification technologies. This gap hampers awareness and adoption, particularly among SMEs that may not have internal capacity to assess or implement complex changes in heat supply. An example to learn from here is the Netherlands.

The Netherlands has built a regionally embedded, industry-focused support system for decarbonising process heat that goes far beyond national roadmaps. Through the Versnellingshuis Verduurzaming Industrie ('Acceleration

House')(Versnellingshuisce, 2025), industrial companies (especially SMEs) receive tailored, free technical assistance from experts who understand regional industrial contexts. This is supported by a network of Regional Development Agencies (ROMs) and backed by the Dutch government and industry associations. What sets this model apart is its integration with physical innovation spaces like the Fieldlab Industrial Electrification (FLIE) in Rotterdam, where companies can test and pilot electrification technologies in real-world conditions, supported by technical partners and researchers (Fieldlab, 2025). Unlike systems where guidance remains generic or centralised, the Dutch model offers hands-on, sector-specific, and regionally accessible support embedded within industrial ecosystems, ensuring faster adoption, better alignment with industrial needs, and more effective scaling of electrified heat solutions.

## 4.4 Key recommendations for the deployment of P2H and Storage solutions across all industry sectors

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### 1. Understand current heat demand and processes

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A detailed assessment of heat consumption by process, equipment, and temperature range is essential to establish a baseline and prioritise decarbonisation efforts.

A thermal energy audit should be used to characterise load profiles, peak demand periods, and process-specific heat demand requirements, such as temperature level, type of heat transfer and medium, the operating profile of each process (e.g. batch or continuous), load variability, and response time needs.

This comprehensive understanding of process-specific heat demand will allow companies to determine where electrification or storage solutions can be applied effectively and more economically and to select appropriate electrification and thermal storage solutions. Heat demand mapping also reveals inefficiencies, operating patterns, and variability that can further influence technology selection and system design.

### 2. Identify and assess electrification potential for heating processes

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Different processes (e.g. drying, steam, melting) will require different types of heat and will benefit from different electrification solutions. Once heat demand is understood, each process should be evaluated for its compatibility with mature electric heating

technologies such as heat pumps, resistance heating, or induction systems. Not all processes can be electrified in a cost-effective or technically feasible way, particularly where high temperatures, fast response times, or strict thermal control are needed. Identifying technically viable opportunities ensures that investment is focused where it will deliver the most benefit. This assessment should also account for process constraints, retrofit complexity, and control requirements.

### 3. Evaluate grid connection

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Electrifying industrial heat can lead to substantial increases in electricity demand, which may exceed the capacity of existing electrical infrastructure. If grid constraints are not identified and addressed early, they can result in significant delays or added costs. Planning at the feasibility stage, including a load impact assessment and early engagement with the Distribution System Operator (ESB Networks), helps anticipate connection needs, manage upgrade timelines, and identify any flexibility options that could reduce demand on the grid.

### 4. Investigate opportunities for onsite electricity production

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Integrating onsite renewable electricity generation, such as solar PV or wind, can reduce reliance on the grid, lower operational costs, and increase the carbon savings from heat electrification.

These systems can also help mitigate exposure to volatile electricity prices and improve energy security. A site-specific feasibility study should evaluate available space, resource potential, regulatory factors, and how well the generation profile aligns with heat demand patterns. It should also consider the economics of investing in renewable generation alongside electrification measures, to support integrated planning and identify synergies in cost, design, and operational performance.

## **5. Explore suitable thermal storage solutions**

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Thermal energy storage technologies, such as hot water tanks, packed-bed storage with sand or crushed rock, or other solid media systems, can significantly enhance the flexibility of heat supply. By decoupling heat generation from consumption, TES allows heat to be produced during off-peak hours or when renewable electricity is abundant, reducing peak demand and improving system efficiency.

The choice of storage technology should reflect all technical requirements of the heating processes such as temperature requirements, type of heat transfer, the operating profile, the required response time, discharge duration, load variability, and available space. These factors determine how well the storage system can integrate with existing processes, maintain stable operation, and provide flexibility to optimise energy use and cost.

## **6. Start with pilot projects or modular retrofits**

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Pilot-scale implementations or modular retrofits offer a low-risk way to test electrification and storage solutions. These projects help build internal expertise, provide operational data, and support the development of business cases for broader deployment. Starting with low-temperature or non-critical processes allows easier integration and fewer risks to production. Clear performance monitoring should be planned and put in place to evaluate energy use, system performance, and the impact on process quality and to inform larger scale deployment.

## **7. Upskill workforce**

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Adopting new technologies requires a workforce equipped to operate, maintain, and optimise these systems. A lack of technical knowledge or operational familiarity can slow down or undermine decarbonisation efforts. Training programmes should focus on electricity-powered heating and thermal storage technologies addressing system operation, maintenance needs, safety requirements, digital controls and energy management. Building in-house capabilities not only ensures safe and efficient operation but also supports continuous improvement and adaptation as technologies evolve.

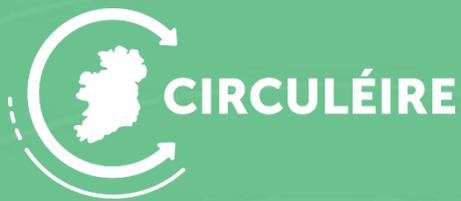
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