Future Opportunities for Electrification to Decarbonise UK Industry

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ERM

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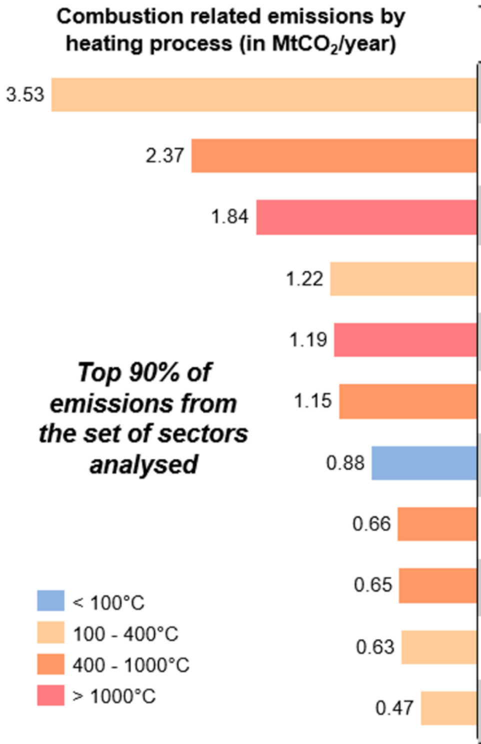
EXECUTIVE SUMMARY

Electrification is one of several solutions that could support decarbonisation of UK industry. Industrial activities in the UK currently contribute around 73 $MtCO_2e$ (or 16%) of the total annual emissions in the UK. The need for deep decarbonisation in industry over the next 20-30 years will be crucial to achieve the UK Government's Net-Zero ambition. Electrification of industrial processes is one of several technological solutions proposed for reducing emissions, with other solutions being carbon capture and storage, fuel-switching to hydrogen or bioenergy, and energy efficiency measures. This study has been commissioned by the UK Government's Department of Energy Security and Net Zero (DESNZ) to improve the evidence base for industrial electrification and to identify the non-fiscal barriers to industry adopting electrification solutions. It follows previous studies on the topics of industrial fuel switching, hydrogen for industrial heating, and hydrogen boilers. The findings from this report will inform policy decisions on industrial decarbonisation and highlight areas for innovation, with the data used to inform technology assumptions for DESNZ industrial energy and decarbonisation modelling.

For most UK industrial heating processes, an electrification alternative can be identified as under development. This study initially considered 10 UK industrial sectors - covering those with the greatest emissions in the National Atmospheric Emissions Inventory (NAEI) point source database. Through researching the processes within these sectors, it was concluded that the majority of emissions were associated with combustion of fossil-fuels for heat generation (with temperature requirements ranging from less than 100°C to more than 1000°C).



Heating Process	Electrification technologies
Steam Generation	Compression Heat Pump, Electric boiler, MVR
Pyrolysis Steam Cracker	Electric Cracker
Calcination and Sintering	Plasma Furnace, Electric Arc Calciner
Atmospheric Distillation Unit	Resistance Furnace
Glass Melting Furnace	Resistance Furnace
Hydrogen Production SMR	Resistance Furnace
Space Heating	Compression Heat Pump, Electric Boiler
Clinker Pre-heating	Resistance Kiln
Brick Firing Kiln	Resistance Kilns, Microwave-assisted Kiln
Ovens	Microwave / Infrared Dryer
Catalytic Reforming	Resistance Furnace

Figure E1: Depiction of the combustion emissions from heating processes and the associated electrification technologies that could abate these processes (data available in Table 5 of the appendix).

A review of the literature on electrification technologies revealed that established techniques exist to generate such temperature ranges electrically, including heat-pumps, resistive heating, electromagnetic radiation, and electric arc. While currently the applications of such techniques to specific industrial processes are limited, this study identified that in many areas there exists ongoing research to demonstrate and commercialise electrified heating solutions. Furthermore, some heating applications (such as steam generation) already have a commercially available electric option.

This study provides detailed analysis of electrification opportunities for seven major industrial heating processes. To understand the technical potential of electrification for UK industry, engineering analysis was conducted on a shortlist of seven industrial heating processes (detailed below). The shortlist covered major emission sources across six distinct sectors, in addition to steam generation that is cross-sectoral. These processes within these sectors alone are estimated to account for at least 11 $MtCO_2$ of UK industrial emissions (considering NAEI point source emissions). The engineering analysis aimed to identify the technical capabilities of proposed electric solutions in comparison to conventional technologies, understand the technical and commercial readiness of electric solutions, and identify non-fiscal barriers to adoption. The analysis concluded in providing technical recommendations for increasing the technical maturity and/or wider uptake of electric technologies in UK industries. **These findings are summarised below:**

Electrification opportunities for UK sectors

Cross sectoral – Electric boilers for Steam generation: Steam generation is present across multiple industrial sectors. Typically, a gas-fired boiler is used to produce low, medium or high-pressure steam between 100°C to 550°C and 2 barg to 160 barg. Boilers can be electrified using resistive heating element boilers or electrode boilers (typically used for larger scale applications). Electric boiler technology has reached a technical readiness level (TRL) of 9 and commercial readiness indicator (CRI) of 6. To enable the uptake of this technology, the following actions were identified:

RESEARCH: There are no apparent innovation needs to develop electric boiler technology.

DEMONSTRATION: Demonstrations are mainly required to display the capabilities of electric boilers (particularly electrode boilers) in large industrial applications with high-pressure steam requirements.

WIDER: Raise wider industry awareness of the capabilities of element and electrode boilers for low and medium pressure steam generation.

Paper – High-temperature heat pumps for Steam Generation: In paper production mills, combined-heat-and-power (CHP) plants are used to provide electricity and low-pressure steam, between 150°C to 180°C and < 3 barg, to the drying section of a paper machine. High-temperature heat pumps (HTHPs) and mechanical vapour recompression (MVR) are under development for this heating application and both technologies are currently rated as TRL 7-9 and CRI 2-4 in the literature. To enable the further development and uptake of this technology, the following actions were identified:

RESEARCH: Conduct further testing and research into identifying refrigerants with low global warming potentials to reduce concerns around the potential impacts of refrigerant leakage. Capitalise on learnings from existing MVR applications in paper production and other industries to understand how the technology can be best integrated with HTHP technologies to cover the range of temperature requirements across a paper site.

DEMONSTRATION: Demonstrate the use of high-temperature heat pumps at scales relevant to the paper industry (10s of MW_{th}) to provide reassurance to adopters that the technology can meet the requirements of the paper industry as claimed. Demonstration of HTHP and MVR technologies for steam production is particularly important to communicate the capabilities of the technologies in an application where there is low industrial awareness.

WIDER: Exploit opportunities to deploy commercially available heat pump products by supporting the paper industry to identify appropriate products that meet site-specific requirements

Olefins – electric cracker for pyrolysis steam cracking: In olefins production, pyrolysis steam cracking furnaces are used to produce olefin hydrocarbons at temperatures between 750°C and

950°C. An alternative technology in the literature was identified as an electric resistance cracking furnace, which are still under technical and commercial development (TRL 6 and CRI 1). To enable the further development and uptake of this technology, the following actions were identified:

- **RESEARCH:** Conduct further research into the design concept for an electric cracking reactor, including how to meet final cracking temperature, product yield and quality requirements
- **DEMONSTRATION:** Monitor the results of current international first-of-a-kind (FOAK) consortium projects to establish further areas of technological development (BASF & SABIC, Shell & Dow)
- **WIDER:** Identify alternative uses for the by-product fuel gases to support the case for electrification (in comparison to carbon capture). Explore how implementation of electric crackers may impact wider plant operations and establish process integration requirements.

Cement – Electric arc calciner for calcination and sintering: In cement production, fired pre-calciners and rotary kilns are used to decompose limestone into lime and produce clinker at very high temperatures of around 900°C (pre-calciner) and 1400°C (rotary kiln). Electric arc calciners were identified in the literature and stakeholder engagement as a rapidly developing alternative technology, with a TRL 5-6 and CRI 1-2. To enable the further development and uptake of this technology, the following actions were identified:

- **RESEARCH:** Support research directed at scaling-up the design of individual reactors, particularly the plasma arc torch component, to meet the requirements of current production levels with a realistic number of units.
- **DEMONSTRATION:** Monitor outcomes of wider demonstration projects linked to electric arc calciners. Particularly, the Electric Calciner Research Centre in Hofors, Sweden opening in autumn 2023 and the SMA Mineral Zero Emissions Quicklime factory, expected for completion in 2025.
- **WIDER:** Improve awareness around electrification technologies through targeted studies to provide a strong demand signal that incentivises research and development in this technology.

Refining – resistance furnace for atmospheric distillation unit: In oil refining, the atmospheric distillation unit (ADU) is powered by a large gas-fired process heater, reaching temperatures of almost 400°C. An alternative heating technology was identified in the literature as electric resistance furnaces which are still under technical and commercial development (TRL 6 and CRI 1). To enable the further development and uptake of this technology, the following actions were identified:

- **RESEARCH:** Conduct research into the design concept for integration of resistive heating into refinery furnaces, including the ADU process, and deploy pilot-scale trials to validate large resistive heating systems and improve TRL (currently TRL 6). Target research to address key issues with lifetime of resistive heating elements to improve confidence in applications where reliability is paramount.
- **DEMONSTRATION:** Monitor outcomes of wider demonstration projects linked to high-temperature electric resistive heating (e.g., steam cracking). Following further technical research, conduct demonstration projects that show integration of resistive heating into ADUs.
- **WIDER:** Identify alternative uses for refinery off-gases to support the case for fuel switching away from internal fuels via furnace electrification (in comparison to carbon capture).

Glass – Resistance furnace for glass melting: In the glass sector, regenerative cross-fired furnaces are used to melt glass at temperature close to 1700°C. Two alternative technologies were identified in the literature, namely; cold-top vertical melting furnace (for container glass) or an electric hybrid glass melting furnace (for flat glass), both of which are technologically and commercially developed (TRL 9 and CRI 6). To enable the uptake of this technology, the following actions were identified:

RESEARCH: Utilise computational modelling to improve the design of larger furnaces and their ability to control thermal flows within the glass-melt. Direct material research efforts towards developing refractories that are more resistant to wear and corrosion, increasing the campaign life of electric furnaces. Computational modelling can help operators understand where best to reinforce and maintain tank walls relative to conventional maintenance techniques. Continue research investigating techniques to maintain batch blanket stability for glass types (particularly amber glass) that are susceptible to foaming and gas eruptions.

DEMONSTRATION: Support UK demonstration projects to provide learnings and develop skills around wider integration of technologies into existing facilities.

WIDER: Improve awareness of the capabilities and benefits of cold-top vertical melting (CTVM) furnaces and hybrid glass melting furnaces. Research into the combination of complementary abatement technologies such a hydrogen will help to completely decarbonise the heating of hybrid furnaces. Raise further awareness that the smaller capacities of CTVM furnaces presents an opportunity for multiple smaller furnace installations, providing improved process flexibility and economic feasibility of operation.

Food & drink – Microwave technology for oven/dryer: In the food & drink sector, gas-fired baking ovens are used on some sites to cook and/or dry food products. These ovens typically operate in the temperature range of 100°C to 300°C. An alternative technology was identified in the literature as microwave ovens, which are an established technology already used for some food products (TRL 8-9 and CRI 1-2). To enable the further uptake of this technology, the following actions were identified.

RESEARCH: Support application specific testing (e.g., lab and pilot projects) to establish the suitability of microwave heating for specific product applications, specifically with regards to understanding the impact on product quality. Identify any techniques that can be employed to complement microwave technologies in meeting specific product quality requirements.

DEMONSTRATION: While technologies are already established, incentivising sites to become early adopters could enable the development of learnings and skills around wider integration of technologies into existing facilities. These pilot testing projects should aim to study particular areas of concern for the food & drink industry, including: effects on product quality, reliability and ease of integration into existing industrial manufacturing lines.

WIDER: Raise wider industry awareness of the capabilities of microwave heating technology for typical baking/drying processes and highlight the productivity benefits from the technology.

Wider benefits of deploying electrification

There are several benefits shared among the industrial sectors and processes that deploy electrification technologies to replace the incumbent heating processes.

Environmental: The electrification of industrial heat eliminates virtually all direct emissions of carbon and air pollutants (scope 1) from combustion. As the electricity grid intensity approaches net-zero by 2035 – in line with government ambition – electrified processes can also eliminate scope 2 emissions from electricity purchases. While electrification has a high potential to remove emissions associated with providing industrial heat, it may not be able to fully eliminate process emissions that are produced by chemical reactions (other than combustion) intrinsic to the sector. Electrification can complement carbon capture systems that aim to remove these process emissions. By replacing combustion heating systems, the combustion flue streams with low CO_2 concentrations are removed, leaving behind only the high purity process emissions streams which are more easily captured by carbon capture plants.

Efficiency and product quality: For many electrification technologies, such as electromagnetic radiation and electric arc, the heat supplied by electricity can be more precisely focused and is often easier to control than a high-temperature flame. Furthermore, electric heating systems do not waste heat from waste combustion gases. These benefits allow for more efficient heating and in some cases, improvements in product quality.

Operational benefits: Electrification can vastly improve processing times, thereby reducing overall production costs even with higher energy costs from electricity. Furthermore, some electric technologies (like resistance heaters) can be deployed in a modular way.

System benefits: Electrification can reduce issues of energy security from single-fuel dependency. Furthermore, it may enable additional benefits for the wider power system when coupled with thermal energy storage (TES) systems or batch operating profiles.

Dispersed sites: For industrial sites in remote locations (such as those in cement, glass, and food & drink sectors) or sites unable to connect to a nearby industrial cluster due to capacity constraints; electrification offers a decarbonisation solution that builds upon existing energy infrastructure more readily accessible to the sites (albeit with a potentially reinforced connection, which will require further investigation and / or investment).

Wider barriers of deploying electrification

implementation of electrified technologies is not without barriers. The most significant of these are likely to require centralised government action to create the enabling conditions for industrial sites and low-carbon project developers to enact their electrification plans:

Upfront cost: Due to the low commercial penetration for most electrification solutions, these technologies often face very high upfront costs to replace the existing direct fuel equipment. Furthermore, the combustion assets of many industrial sites still have many years of useful life left therefore creating a barrier of sunk costs.

Process modification cost: Electrification can undo the complex process and heat integration used in many processes. Therefore, in addition to technical maturity, electrification solutions need to produce an overall energetically efficient way to replace the incumbent technology.

Cost of electricity: The cost of heating industrial process is primarily driven by the cost of energy. Currently in the UK, the average cost of electricity for industrial customers is around four times more expensive than the cost of gas fuel for the counterfactual heating processes.

Grid infrastructure requirements: Large-scale electrification projects rapidly increase the connected load seen on the network. In grid-constrained areas, a single electrification project could necessitate significant investments through new substation transformers and other grid reinforcement measures.

Lack of knowledge: The lack of comparative expertise in electrification technologies increases its perceived risk to replacing incumbent heating technologies. This creates the impression amongst industrial companies that they are not mature or suitable for use in their processes.

Electrification value chain: There may be a potential supply chain risk for certain mature electrification technologies (like heat pumps and electric boilers) which may see a rapid increase in demand from industries.

Limited renewable penetration: The current backlog in renewable generation projects threatens to delay the speed of decarbonisation of the power grid. This therefore delays the environmental incentive to deploy electrification technologies.

Competing decarbonisation pathways in industrial clusters: The UK Government CCUS Cluster Sequencing programme may act as an incentive for sites within industrial clusters to preferentially deploy carbon capture or fuel-switch to hydrogen, as an alternative to electrification. However, electrification is still expected to play a role in decarbonising industrial clusters. For example, it might benefit sites:

- That would not meet the CO_2 specifications of shared infrastructure (e.g., purity) or would have to invest significantly to meet these
- That are too small in scale to economically deploy carbon capture or connect to shared infrastructure
- Where electrification offers other benefits over hydrogen or CCS (such as modularity or process improvements)

1 INTRODUCTION

1.1 Background

Several studies have previously investigated the technological options for decarbonising UK industry and the likely uptake of these technologies. These include studies on the topics of industrial fuel switching, hydrogen for industrial heating, and hydrogen boilers, as well as UK wide modelling of technology uptake using the Net Zero Industry Pathways (N-ZIP) model. The data in this past work that pertains to opportunities for electrification of UK industry is however limited and potentially outdated, given the rapid, ongoing developments in electrification technologies. This study has therefore been commissioned by the UK Government's **Department of Energy Security and Net Zero** (DESNZ) to improve the evidence base for opportunities to electrify emission intensive industries in the UK and to identify the non-fiscal barriers to industry adopting electrification solutions. The study is aimed at providing up-to-date decarbonisation technology data that covers the breadth of available technologies, considers long-term development potential, and is aligned with industry trends. It will be used by DESNZ to inform policy decisions on industrial decarbonisation and highlight areas for innovation, with the data collated used to inform technology assumptions for DESNZ industrial energy and decarbonisation modelling.

1.2 Objectives

The key objectives of this work are to:

- Identify future electrification options for the most significant industrial sectors and processes, gather key metrics, and discuss the strengths and weaknesses for each option
- Identify innovation needs for technologies identified with greatest potential, and provide distinctions between electrification opportunities based upon technical and commercial readiness
- Identify wider technological barriers and benefits to electrification and to establish a high-level comparison with other decarbonisation options

To meet the objectives, key data metrics will be gathered for each electrification technology, with a focus on the future technical potential, considering:

- Suitability of electrification options to different industrial sectors
- Electrification options in terms of their technological and commercial maturity and needs for innovation.
- Barriers and benefits of electrification options
- System-level considerations and interdependencies

1.3 Study scope and approach

The scope of the study was constrained to focus on opportunities for **directly electrifying heating processes** for emission intensive industries in the UK. It is noted that electrification can play a broader role in industrial decarbonisation, with wider examples being: electrolysers for hydrogen production or the replacement of combustion driven shaft work with electric motors. These opportunities were not considered within the scope of this study, noting that electric motors and electrolyser technologies are already well developed and understood by the industry.

The approach to this study was broken up into the following five components:

- **Literature review to scope and screen opportunities for electrification options**: In this task, an initial analysis of UK industrial CO_2 emissions was conducted to identify sectors with the largest carbon reduction potential. A review of public databases and reports was then used to characterise these sectors by their current heating processes and understand their energy consumption and fuel use. An extensive literature review was also conducted to summarise the currently accepted views on what industrial applications are electrifiable. After consultation with DESNZ, a shortlist of electrification opportunities was selected for deeper assessment.

- **Engineering analysis to evaluate the identified electrification options:** The ongoing literature review was streamlined to gather key data metrics for each electrification option, based on academic and commercial literature; and to identify general strengths and weaknesses of the selected electrification options compared to the incumbent fossil-fuel based appliances.
- **Maturity assessment of electrification options and alternatives:** An assessment of the technology maturity of electrification options was conducted, including identification of sector specific barriers, innovation needs and recommendations for enabling deployment
- **Wider barriers and benefits for electrification:** To supplement the engineering analysis, the wider technological barriers and benefits to electrification were assessed qualitatively.
- Targeted stakeholder engagement was used to validate and supplement the findings throughout the study.

2 ELECTRIFICATION FUNDAMENTALS

This study focuses on assessing technological opportunities for **electrifying heating processes** in major UK industrial applications as an alternative to combustion of fossil fuels. While each electric heating technology may be developed to address application specific requirements, the method of utilising electricity to provide heat can be summarised into four fundamental approaches: **heat pumps, resistive heating, electromagnetic radiation, and electric arc**. An overview of each of these approaches is provided below, alongside a general characterisation of applicability to different heating applications. It must be noted that there are several published reports that describe the electrification of industrial heat. In these reports, a section dedicated to the explanation of the fundamental electrification approaches listed above is usually seen. For this study, a similar approach was used to describe, at a high-level, what these general electrification technology categories are, before the individual discussions on the electrification of specific heating processes. As such, the following reports are acknowledged for their influence on the content in these overviews:

- Harnessing heat pumps for net zero (Australian Alliance for Energy Productivity – A2EP)[1]
- Zero Carbon Industry Plan: Electrifying Industry (Beyond Zero Emissions)[2]
- Electrifying Industrial Heat: A Trillion Euro Opportunity Hiding in Plain Sight (Ambienta Sustainability Lens)[3]
- Improving Process Heating System Performance: A Sourcebook for Industry (U.S. Department of Energy)[4]

2.1 Heat pumps

Heat pumps are technologies which use electricity to transfer heat from a heat source – air, ground, water, waste heat – to a heat sinking process – production of hot air, water, or steam. These technologies differ to the conventional heating technologies of gas or electric resistive boilers in that they use electricity to 'move' heat, rather than generating heat from electricity. This allows heat pumps to transfer more energy (heat) than is expended in physically driving the cycle using electricity, due to the principle of exergy.[*]

In heat pump operation, the heat source and heat sink are brought together through the compression and expansion of a working fluid – refrigerant – capturing the heat from the source (ground, water, air or waste heat) and 'dumping' it in the sink. The same principle governs the operation of household refrigeration, in that heat is extracted, moved from the source (environment inside the refrigerator) and discharged to the heat sink (the environment surrounding the refrigerator). The configuration of the heat source/sink and the compression-expansion stages can vary widely depending on the particular application. In general, this heat transfer process can be separated into the following stages, depicted in Figure 1:

1. **Evaporation:** the liquid refrigerant is passed through a heat exchanger, where it absorbs the heat from the source at a temperature higher than its boiling point, thereby converting the liquid to gas.
2. **Compression:** The temperature of the gaseous refrigerant is then significantly increased by a passing through an electrically driven compressor.
3. **Condensation:** The 'hot' gaseous refrigerant, at a temperature above the required application temperature, is subsequently passed through a heat exchanger (condenser), where it releases its heat to the heat transfer fluid of the required application (air, water, oil

[*] Exergy is simply a measure of the quality or the ability to do useful work of a given energy source, making a useful distinction between the magnitude (megawatts) of different energy vectors. Thermal energy (heat) is intrinsically of a lower quality (exergy) than other forms of energy such as electrical or mechanical drive.

etc) and in so doing condenses back to the liquid phase which is still at an increased temperature and pressure from the compression stage.

4. **Expansion:** in this stage, the liquid refrigerant is passed through an expansion valve such that its temperature and pressure are reduced to the levels suitable for the evaporation stage as the cycle repeats again.

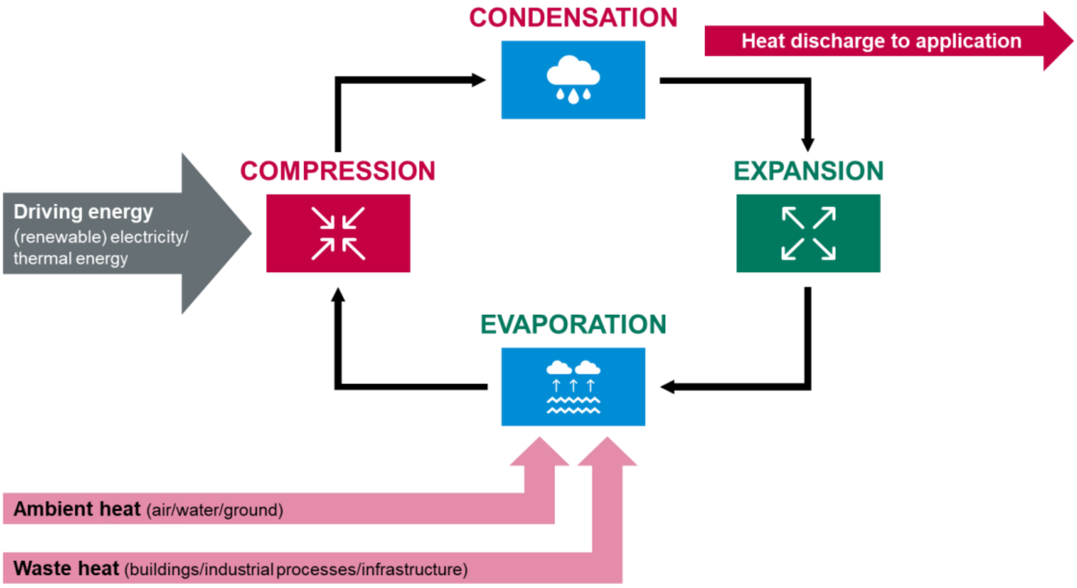


Figure 1: Illustration of typical components and operation of a heat pump as described in the text (adapted from Harnessing heat pumps for net zero[1])

The type of refrigerant used in the heat pump cycle governs its ability to transfer heat from the source to the sink. The refrigerants used in these heat pumps are usually characterised by having a low boiling point temperature. Not all heat pump cycles use a refrigerant, particularly for geothermal heat pump systems. These systems can circulate a refrigerant within closed loop of underground pipes or submerged water, also known as a closed-loop heat pump. Alternatively, a groundwater source can be pumped directly through a heat pump which extracts its heat and discharges in back into the ground or some other reservoir.

The performance of a heat pump is measured by its efficiency, or coefficient of performance (COP), which represents the ratio of thermal output to electrical input. As mentioned earlier, because heat pumps use electricity to transfer, rather than generate, heat, they can deliver more heat than the electrical energy required to power the cycle. Heat pumps typically reach a COP greater than 3, compared to gas or other electrical heating appliances which cannot physically reach a COP greater than 1 (efficiency of 100%).

Heat pumps have traditionally been used for space heating applications for the residential and commercial sectors meaning that they upgrade the heat source (air, groundwater) from ambient temperature conditions to temperatures around 50-60°C. However, for higher temperature industrial heating processes, high-temperature heat pumps are being established to upgrade heat to temperatures close to 200°C with a COP of up to 7. These technologies often use different refrigerants, a higher temperature heat source and more complex thermodynamic cycles.

2.2 Resistance heating

Resistance heating has been a reliable form of heating for well over a century, used for both domestic and industrial applications. For example, in household kettles or resistance heaters. This method of heating simply involves passing an electrical current through a material that has some resistance to electron flow, creating heat within the material. Generally, electrical resistive heating falls under the two following categories:

- **Direct resistance:** The electrical current flows through the target material (or charge) and heats it directly, utilising the Joule law. In these systems, there is direct contact between the material and the electrodes within a heating chamber which are then charged with an electric current, thereby generating heat within the material due to its electric resistance. By adjusting the current, direct, or alternating (DC or AC), the temperature and power can be controlled. The target material used in these systems must have a low conductivity such that it allows electric current to pass through but still have a high resistance to produce the required heating load. This technique is mostly used for heat treating, forging, extruding, glass heating and melting as well as other applications.[4]
- **Indirect resistance:** Here there is no contact between the hot resistive heating element and the target material. Instead, heat is transferred from the hot element to the material via conductive, convective or radiative heat transfer. The heating element is usually made of a high-resistance material such has graphite, nickel chrome or silicon carbide. Heating in this way occurs in a heating chamber, typically lined with ceramic, brick and fibre batting. The interior environment of these furnaces can be comprised of air, inert gases, or a vacuum in some cases.

Resistance heating technologies are favoured for their simple design and high efficiencies of up to almost 100%. Furthermore, these technologies have low maintenance requirements, high controllability (due to their compatibility with modern electronic systems) and can reach temperatures up 2,400°C.[3] Resistance heating technologies have already been widely used in low and high temperature heating applications across multiple industrial sectors such as food, chemicals, plastics, glass and steel.

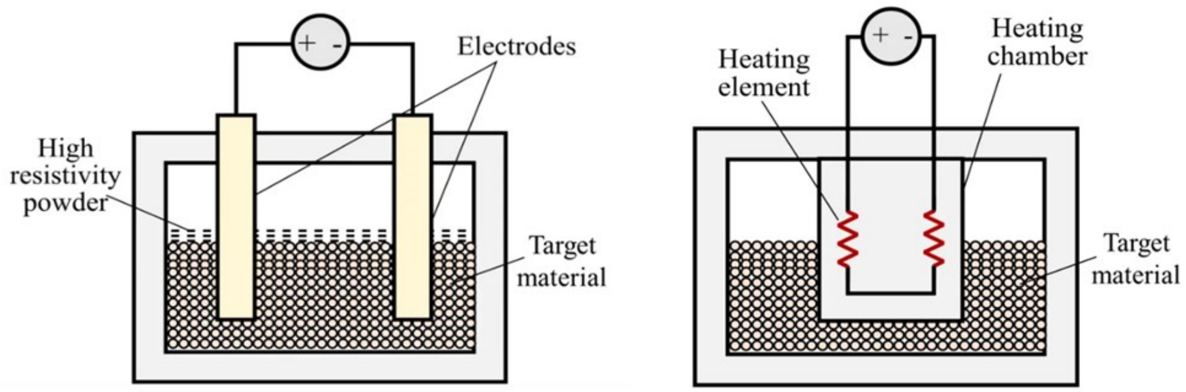


Figure 2: A simplified illustration of direct (left) and indirect (right) resistance heating method[5] as described in the text

2.3 Electromagnetic radiation

Electromagnetic radiative heating relies on the conversion of electricity into electromagnetic radiation at different wavelengths (or frequencies) in the electromagnetic spectrum. Household and commercial microwave ovens employ this principle to heat food. These technologies have been well established in industrial heating applications for decades. The generated radiation can be used to deliver heat at temperatures up to 3000°C.[3] The main advantage of these technologies is the more efficient way (compared to combustion) of generating heat within a target material, instead of first heating an intermediate medium which then transfers heat to the target material through convection. Electromagnetic technologies have several other advantages, including rapid heating (faster than other electric technologies), precise control of heat localisation, reduced physical footprint, higher safety, and decreased material waste.[2] Each wavelength of electromagnetic radiation has its own applications, as shown by Table 1.

Table 1: Table summarising different electromagnetic radiation technology types as described in the text (adapted from Beyond Net Zero[2])

Technology Type	Induction	Radio	Microwave	Infrared
Max temp (°C)	3,000	2,000	2,000	2,200
Power density* (kW/m^2)	50,000	100	500	300
Efficiency	50-90%	80%	80%	60-90%
Application	Rapid internal heating of metals	Rapid internal heating of large volumnes	Rapid internal heating of large volumes	Very rapid heating of surfaces and thin material

**Power density signifies the rate of energy transfer to an amount of material. Increasing power density enables increases in productivity*

- **Induction heating** is associated with the longest wavelength of electromagnetic radiation and has been used in industry for almost a century in metal processing applications (melting, hardening, etc.) This method of heating is a non-contact way to heat electrically conductive materials like metals. Heat is generated by inducing an electric current within the target material by exposing it to an electromagnetic field. This is done by positioning the target material within a metal coil, through which, a high-frequency electric current flows and creates electromagnetic field around the target material. Induction heating can reach high temperatures of up to 3000°C and is often the preferred method of heating metal because it is faster and more efficient than either fossil-fired or other electric furnaces.[2]
- **Radio-frequency and microwave radiation** fall under the category of dielectric heating. In these systems, the target material is also exposed to an electromagnetic field. Unlike induction heating, this method is very well suited to non-conductive materials such as paper, textiles, and wood. These materials contain molecules with distinctively positive or negatively charged poles. When exposed to an electromagnetic field, these molecules thus change their alignment within the material. Dielectric systems function by generating a rapidly alternating electromagnetic field such that the molecules within the target material move synchronously and through their friction, create heat.[4] Radio-frequency heating techniques have a deeper and more uniform heat penetration within the material and are useful for heating materials of a simple and regular shape. Microwave techniques tend to be more expensive but are useful for the rapid internal heating of irregularly shaped materials.
- **Electrical infrared systems** have also been well-established in industry for almost a century, emitting the same infrared radiation that the sun uses to warm the earth. These systems are generally comprised of the following components: an emitter, which is the temperature source; a reflector system that directs the radiation towards the target material; and an application-specific control system.[4] Infrared heating is a very rapid and efficient (up to 95%, depending on wavelength) technology for heating surfaces of materials of a simple shape and flat surfaces. These systems can be designed to reach temperatures as high as 2000°C with a very high-power density.[2]
- **Ultraviolet** processing is another surface heating technology, predominately used for coating applications to provide improved durability, protection, and appearance for consumer products. The UV radiation is typically creating by using a high-voltage discharge to ionize a mercury gas-

filled tube. UV radiation can also be created by using microwave radiation to induce and arc between two electrodes or alternatively using solid state light emitting diode devices.

2.4 Electric arc

Electric arc technologies have been an established technology used to melt metals for several decades. These technologies involve powering a set of electrodes using direct current or alternating current at a very high voltage. In this way, an arc is formed between the electrodes which can be applied directly to a target material, usually a metal.

- **Direct arc furnaces** commonly have a water-cooled refractory-lined vessel, covered by a retractable roof into which graphite or carbon electrodes protrude into the furnace.[4] There is an adjustable distance between the melt surface of the target material and the electrode tips. In this furnace, the charged metal is heated both by the current passing through the arc between the metal and the electrodes and the radiative energy from the arc. These technologies are reliant on control systems which maintain a suitable current and power input during the melting process as well as regulating the arc by moving the electrodes up and down. These furnaces have been in use for many years in the steel industry to melt scrap.
- **In indirect arc heating,** the furnaces commonly have a horizontal barrel-shaped steel shell, which is lined with refractory.[4] Two carbon electrodes are positioned above the charged metal, and with high-voltage current passing through, an arc is struck between the electrodes. The heat from the arc is transferred to the metal being melted by radiation. To increase efficiency and avoid the overheating of the refractory above the melting metal, an alternating rotating motion is applied to the furnace shell. These furnaces are commonly used in the production of copper alloys and are significantly smaller than direct arc furnaces.[2]

The number and type of electrodes used in a furnace depend on the given industrial application. There are also furnaces in which the electrodes are positioned very deep into the furnace and the heating process occurs at the electrode tips. These are called submerged arc furnaces and are used to produce metals such as silicon and iron alloys.

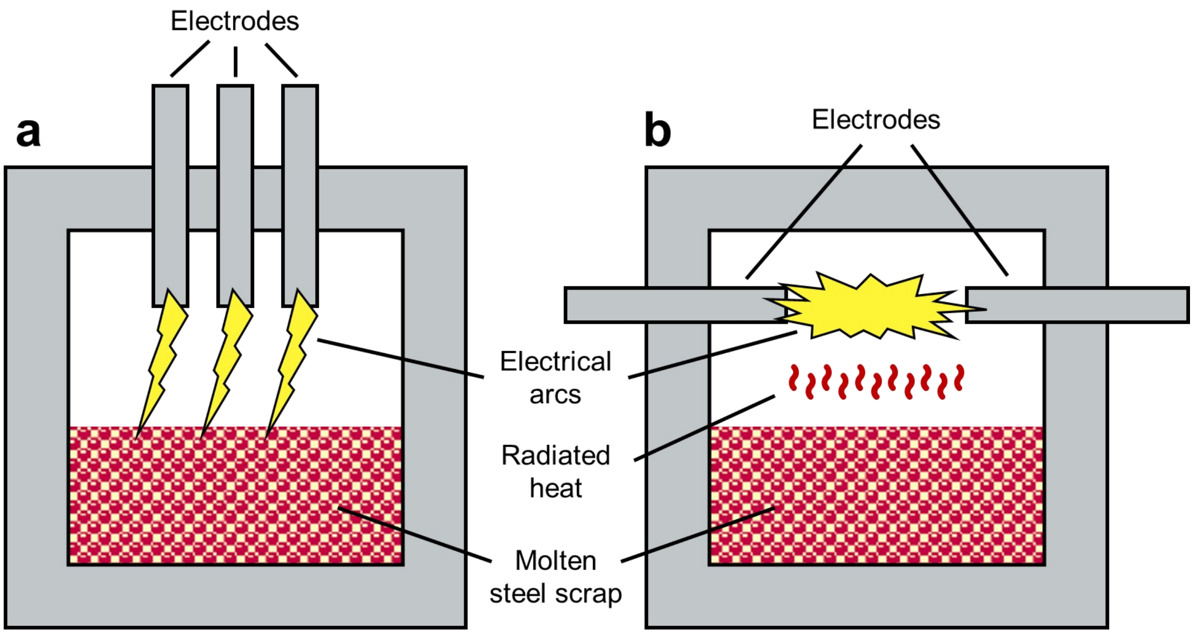


Figure 3: A simplified illustration of (a) direct and (b) indirect electric arc furnaces[6] as described in the text

3 OVERVIEW OF UK INDUSTRIAL ELECTRIFICATION OPPORTUNITIES

UK industrial emissions for major emitting sites are reported within the National Atmospheric Emissions Inventory (NAEI) database for point source emitters. Analysis of the 2021 NAEI point source database including the scale of emissions and number of sites across various subsectors* is shown in Figure 4 below (shown in tabular form in Table 4 in the appendix). It must be noted that the emissions reported in the NAEI point source database account for roughly 59% (43 $MtCO_2e$/year) of the total annual emissions from UK manufacturing activities (roughly 73 $MtCO_2e$/year).[7]

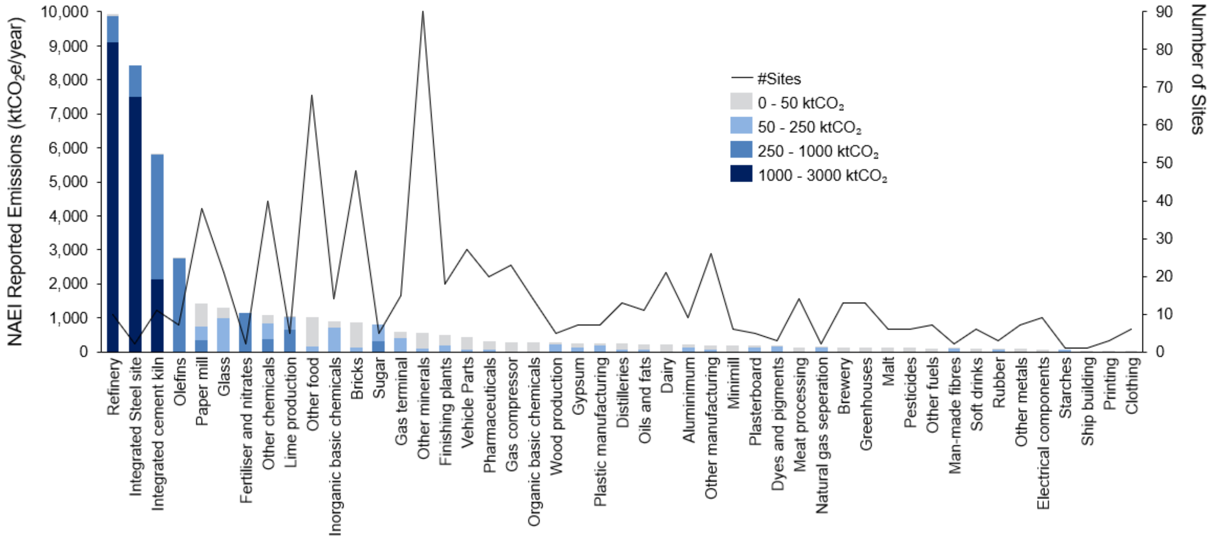


Figure 4: Diagram showing the total reported carbon dioxide emissions on the NAEI database for each industrial subsector[8] (data available in Table 4 of appendix)

This analysis indicates that the industrial sectors with greatest emissions in the UK are refineries, integrated steel sites, integrated cement kilns, and olefins - these account for roughly 62% of industrial emissions reported in the NAEI database. Emissions in these sectors are concentrated amongst a few large sites (>250 $ktCO_2e$ / year per site). Therefore, while developing electrification options for these sectors could provide highly targeted abatement opportunities, there is a risk that such electrification technologies may become less relevant if this proportionally small number of sites commit to alternative decarbonisation routes, such as carbon capture or fuel-switching to low-carbon fuels.

The analysis also indicates that the industrial sectors with the greatest number of emissions point source sites (identified via their existence in NAEI) are Other Minerals, Other Food, Bricks, and Other Chemicals. These sites may be located in more dispersed locations and site-level emissions are typically reported at levels of < 50 $ktCO_2e$ / year. Developing electrification options for these sectors could support wider industrial decarbonisation across the UK by identifying opportunities for more sites than selected major emitters. To make a significant impact on UK emissions, electrification within these sectors of lower site-level emissions would require many sites to adopt electrification technologies.

To focus the analysis of this study, an initial shortlist of sectors for investigation was developed to include the top 10 sectors by total emissions and the top 10 sectors by number of sites (within the NAEI point source database). It was decided to exclude integrated iron and steel sites from the shortlist since there are only two such sites (owned by Tata Steel and British Steel) and there is already good awareness of the potential indirect (hydrogen direct reduced iron, H-DRI) and direct (Electric Arc Furnace) electrification opportunities for this industry in the UK. After excluding the iron

* For the purposes of this analysis, a more detailed categorisation than the standard NAEI sectors was used to assign each site to a subsector based on the expected operation and products produced at the site.

and steel sector, the list was further refined through discussions with DESNZ to select 10 sectors that would provide a focus for understanding the main types of heating processes across UK industry. These 10 sectors represented approximately 35% of the UK industrial emissions and 262 industrial sites (roughly 60% of the emissions reported on the NAEI large point source database) – see Table 2 and Figure 6 for details.

Table 2: Shortlisted industrial subsectors for process archetyping.

	ERM Subsector	NAEI Sector	Emissions ($ktCO_2e$/year)	# sites
1	Oil refining	Processing & distribution of petroleum products	9,932	8
2	Integrated cement kiln	Cement	5,821	11
3	Olefins	Chemical Industry	2,785	4
4	Paper mill	Paper, printing & publishing industries	1,430	38
5	Glass	Other mineral industries	1,290	21
6	Food[*]	Food, drink & tobacco industry	1,256	89
7	Fertiliser and Nitrates	Chemical Industry	1,156	2
8	Inorganic basic chemicals	Chemical Industry	884	14
9	Bricks	Other mineral industries	864	48
10	Vehicle parts	Vehicles	435	27

Using ERM internal expertise as well as research by Maddedu et al.,[9] process archetypes were developed for the shortlisted sectors. These archetypes identify the type of heating processes applicable to each industrial sector and estimate the percentage of combustion emissions that can be attributed to such processes. Each heating process was characterised by operating temperature and grouped into four indicative temperature bands. The results of this archetyping are summarised in Table 3 below. In addition, consideration was given to sectors where significant emissions arise from process emissions – emissions in which CO_2 is produced as a product of a reaction other than combustion. Process emissions were removed from the electrification opportunity assessment as these non-combustion emissions cannot be abated by electrifying heating processes.

[*] The 'Food' Sector includes the dairy subsector.

Table 3: Combustion heating processes classified by temperature band and each industrial subsector.

Heating process \ Subsector		Refinery	Olefins	Integrated Cement Kiln	Paper Mill	Glass	Food	Fertiliser & Nitrates	Inorganic basic chemicals	Bricks	Vehicle Parts
< 100°C	Space Heating	-	-	x	x	-	x	-	x	-	x
	Thermal Drying	-	-	-	-	-	x	-	x	-	x
100 – 400°C	Steam Generation	x	x	-	x	-	x	-	x	-	x
	Ovens	-	-	-	-	-	x	-	-	-	-
	Polymer Melt/ Extruding	-	-	-	-	-	-	-	x	-	-
	Brick Drying	-	-	-	-	-	-	-	-	x	-
	Haber-Bosch Process	-	-	-	-	-	-	x	-	-	-
	Atmospheric Distillation Unit	x	-	-	-	-	-	-	-	-	-
	Vacuum Distillation Unit	x	-	-	-	-	-	-	-	-	-
	Hydrocracking	x	-	-	-	-	-	-	-	-	-
	Thermal Cracking/ Visbreaking	x	-	-	-	-	-	-	-	-	-
	Catalytic Reforming	x	-	-	-	-	-	-	-	-	-
400 - 1000°C	Clinker Pre-heating	-	-	x	-	-	-	-	-	-	-
	Cracker	-	-	-	-	-	-	-	x	-	-
	Reformer	-	-	-	-	-	-	-	x	-	-
	Paper Lime Production	-	-	-	x	-	-	-	-	-	-
	Annealing Furnace	-	-	-	-	x	-	-	-	-	-
	Brick Firing Kiln	-	-	-	-	-	-	-	-	x	-
	Hydrogen Production SMR	x	-	-	-	-	-	x	-	-	-
	Pyrolysis Steam Cracker	-	x	-	-	-	-	-	-	-	-
> 1000°C	Calcination and Sintering	-	-	x	-	-	-	-	-	-	-
	Glass Melting Furnace	-	-	-	-	x	-	-	-	-	-
	Foundries	-	-	-	-	-	-	-	-	-	x

Industrial sectors with internally produced process emissions

Generally, CO_2 emissions provide a reasonable initial proxy for the magnitude of energy demands at a site; however, it is important to note that a site's emissions may not originate solely from fuel combustion processes. Many industrial sectors involve process emissions in which CO_2 is produced as a product of a reaction other than combustion, some of which are:

- **Cement and Lime:** Calcination of calcium carbonate to calcium oxide – approximately half of site CO_2 emissions.
- **Oil Refining:** Coking, catalytic cracking, and reforming units – approximately a third of a refinery's CO_2 emissions.
- **Ammonia Production:** CO_2 is produced in hydrogen production and is often utilised by integrated urea production plants.
- **Glass melting:** The high-temperature decomposition of raw materials (limestone, dolomite, soda ash) leads to 15-25% of the total emissions in the glass sector.
- **Alcohol Production:** Fermentation reactions produce CO_2 that is often captured and liquified for other food and drink processes.
- **Iron Production:** Oxidation of iron ore in a blast furnace produces CO_2; however, a move away from carbon-based reducing agents can eliminate this.

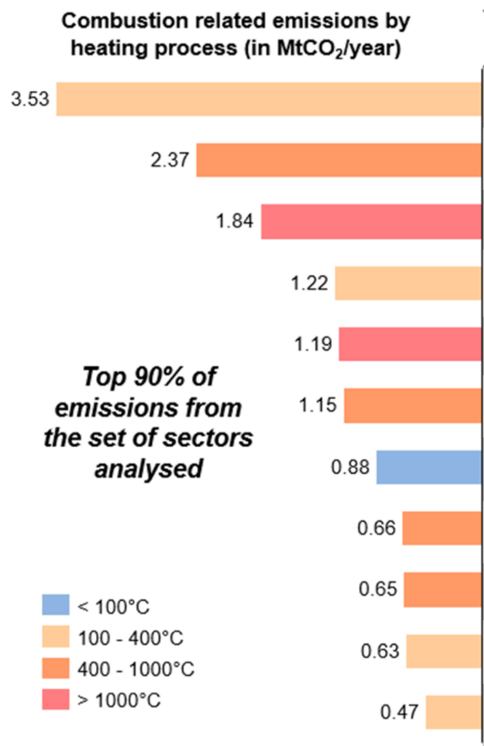
This is relevant because electrification technologies predominantly provide decarbonisation by reducing the need for combustion processes. The potential for electrification to abate other emissions is less consistent and consequently this report focusses on the potential for electrification to reduce emissions from combustion processes. It was estimated that combustion related activities within the shortlisted industrial subsectors contribute approximately 40% of the reported NAEI point source emissions.

For the Cement, Lime, and Refining sectors, few options exist to mitigate the production of process emissions, and these will persist even if the combustion systems at these sites are fuel-switched. Consequently, when investigating the potential for industrial fuel switching, consideration of the influence of process emissions on a sector's likely decarbonisation strategy is pertinent – particularly when there is an opportunity for carbon capture implementation. Carbon capture is most effective on flue streams with high purity CO_2 concentrations. Therefore, electrification of industrial heating processes can complement the implementation of carbon capture at sites with high purity process emission streams by removing the additional technical requirements involved in capturing CO_2 from low purity combustion exhaust emission streams.

Process disruption from fuel switching

Some industrial sectors rely on fossil fuels for chemical feedstock and balance their plant through internal fuel production. This is most significant in the Oil Refining sector where it is not uncommon for a refinery to have a 'balanced slate' meaning that the refinery internally produces all the fuel it requires for combustion from fractions of crude oil. If a refinery decarbonises its combustion systems by fuel switching away from internally produced 'refinery fuel gas', handling of the unutilised refinery fuel gas must be considered and managed. The potential disruption from re-configuring sites with high reliance on internal fuels must be carefully considered when assessing the viability of fuel-switching technologies.

By combining the above analysis, the UK emissions associated with distinct industrial heating applications were estimated. 11 heating processes were identified as being responsible for 90% of the combustion related emissions of the 10 shortlisted sectors (see Figure 5). Roughly 50% of combustion related emissions in this subset of processes arise from heating below 400°C.



Heating Process	Electrification technologies
Steam Generation	Compression Heat Pump, Electric boiler, MVR
Pyrolysis Steam Cracker	Electric Cracker
Calcination and Sintering	Plasma Furnace, Electric Arc Calciner
Atmospheric Distillation Unit	Resistance Furnace
Glass Melting Furnace	Resistance Furnace
Hydrogen Production SMR	Resistance Furnace
Space Heating	Compression Heat Pump, Electric Boiler
Clinker Pre-heating	Resistance Kiln
Brick Firing Kiln	Resistance Kilns, Microwave-assisted Kiln
Ovens	Microwave / Infrared Dryer
Catalytic Reforming	Resistance Furnace

Figure 5: Depiction of combustion-related emissions for each heating process and the associated electrification technologies that could abate these processes (data available in Table 5 of appendix).*

Following an initial literature review into the electrification opportunities for these top 11 heating process, it was found that each of these had at least one potentially applicable electrification technology under development. These results implied that up to 15 $MtCO_2$/year of UK industrial emissions (for 10 shortlisted sectors) could potentially be abated by electrification of industrial heating processes following successful development and commercialisation of known electrification alternatives. To assess this opportunity further, seven heating processes, alongside an identified applicable electrification technology, were subsequently selected for detailed review within this study. The resulting abatement potential for the electrification technologies that apply to these seven processes is roughly 11 $MtCO_2$/year:

- Steam Generation, electric boiler (cross-sectoral)
- Steam Generation, heat pump (paper)
- Pyrolysis Steam Cracker, electric cracker (olefins)
- Calcination and Sintering, electric arc calciner (cement)
- Atmospheric Distillation Unit, resistance furnace (refining)
- Glass Melting Furnace, resistance furnace (glass)
- Oven/Dryer, Microwave Dryer (food and drink)

* It is important to note that many of these processes are also encountered in other, non-shortlisted industrial sectors in the UK and cumulatively amount to significantly more emissions than what is reported here. Information on other heating processes that make up the remaining 10% of combustion emissions is provided in the Appendix.

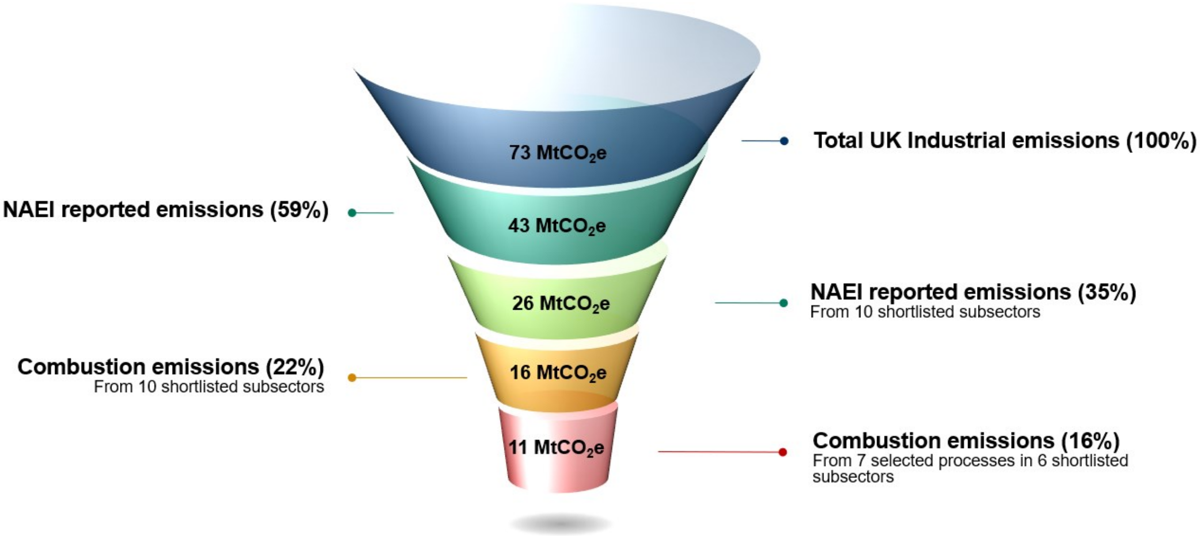


Figure 6: Illustration of the relative emissions contribution at each step of the shortlisting process, described in the text, compared to the total UK Industrial emissions (~73 MtCO_2e / year).

The detailed assessment investigated the incumbent heating technology for the process (within the context of a UK sector) and the applicability of the electric technology alternative, gathering key technology metrics from literature and reporting on application specific benefits or barriers of the electric alternative. The results of these detailed assessments are presented in the following chapter.

4 ELECTRIFICATION OPPORTUNITIES FOR UK SECTORS

The wider sectoral context of selected heating applications alongside the findings of the deep-dive electrification analysis are summarised in sections below. The deep-dive analysis takes the form of, first, understanding the incumbent heating technology (referred to as the “counterfactual”) and then the equivalent electric heating alternative. Data tables comparing the relevant engineering metrics between the incumbent and electric heating technologies are provided. The data provided in these tables reflects the aggregated findings from reviews of literature reports, technology databases and stakeholder engagements. The relative barriers and drivers for deployment are then discussed to highlight the further innovation and/or demonstration requirements for each specific electrification opportunity, with a wider discussion of overarching benefits and barriers compiled in section 4.7.

4.1 Steam generation, cross sectoral

Steam is used extensively by a wide range of industrial processes across many sectors to deliver energy. This energy can be extracted as heat for process use or as mechanical work through a turbine. Steam can be used for heating, controlling temperatures and pressures in chemical processes, drying and concentrating, steam cracking, or distillation. In drying or concentration processes, steam is used to evaporate water, to dry a solid product or to concentrate solids in a solution. Cracking involves heating steam and fuel together at a high pressure to produce lighter fuels. Distillation processes are used to extract specific components out of a complex feedstock.

Equipment that *uses* steam is very diverse and can show substantial differences between industries and is often process-specific. Conversely, equipment that *generates* steam shares broad similarities between different industries and processes. The most common equipment used to generate steam is an industrial boiler – the focus of this section. In a boiler, feed water is heated in a pressure vessel to generate steam. Typically, a burner provides heat to the boiler by combusting a fuel, such as natural gas, LPG, oil or coal. The generated steam is then fed to a distribution system, which delivers steam to the process where it will be used. Pressure reduction valves are sometimes used when processes require lower pressure. As steam is used, it cools and some of it condenses. The condensate is recirculated to the boiler, recovering some heat and reducing the need for feed water make up. Boilers can also be used to produce hot water used in some industrial applications.

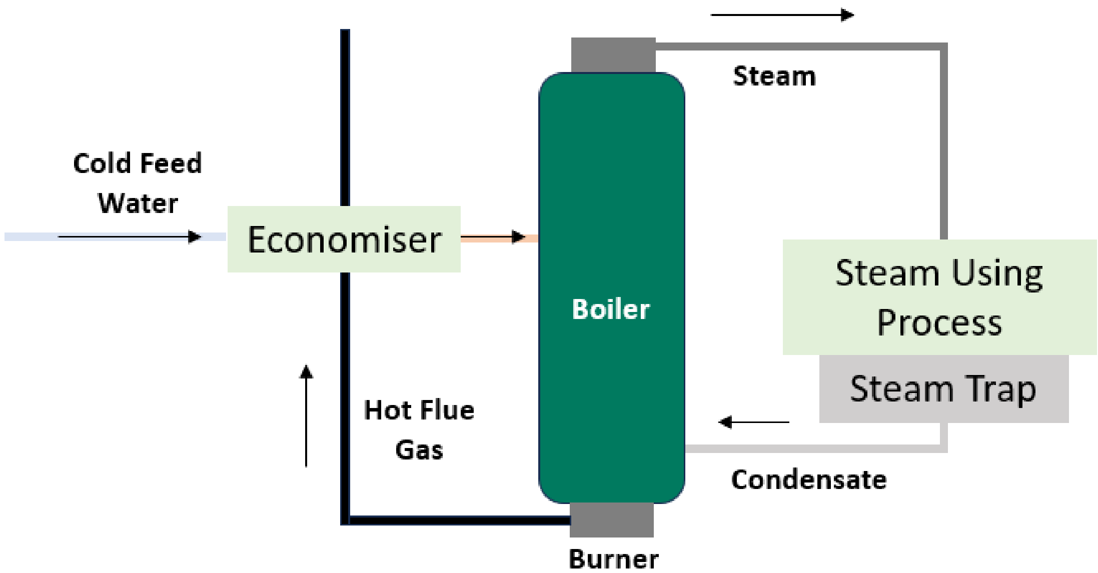
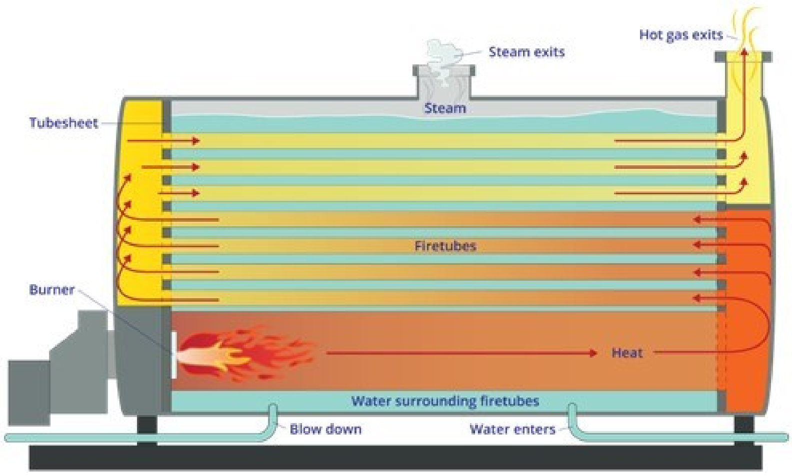


Figure 7: Illustration of a typical steam production and distribution system as described in the text

In the UK, the shortlisted industrial subsectors using steam include: food, inorganic basic chemicals, paper mills, vehicle parts, refineries and olefins. In total, combustion emissions from steam generation for those subsectors are responsible for an estimated 3.5 $MtCO_2$ per year as shown in Figure 5. It is estimated that the total stock of UK industrial boilers (including the excluded sectors) with capacities greater than 1 MW_{th} is approximately 2,000 boilers, with a 70:30 split between steam generation and hot water applications.[10] Based on previous work looking at medium combustion plants (MCP),[11] there are no boilers larger than 50 MW_{th} in England and Wales. Moreover, it is estimated that by 2030 there will be only 13 boilers having a size between 20 and 50 MW_{th}.[12] Depending on the end use for steam, the pressure and temperature requirements can change markedly. These requirements range from some heating processes slightly above 100 °C to superheated steam at 500 °C used for power generation in steam turbines.

Incumbent heating technology – gas-fired boilers

The most common fuel used for industrial boilers in the UK is natural gas. The two main types of boilers available in the market are fire-tube boilers and water-tube boilers. The difference between both types of boilers lies in the way in which water is heated. Water-tube boilers often have larger capacities, higher efficiency, and shorter response times than fire-tube boilers.

Fire-tube boiler	
Description	In fire-tube boilers, or shell boilers, the products of combustion flow though the boiler tube and heat surrounding water housed in a shell. The tube gradually heats the water until it produces steam. The efficiency of a fire-tube boiler is around 80%.[13] An advantage of fire-tube boilers is that they are provided as a single piece of equipment in a 'packaged' arrangement, enabling straightforward installation and maintenance. The pressure and steam output of this boiler type is limited. Multiple units are needed if heat capacity cannot be met by a single boiler.  **Figure 8: Illustration of a Fire-tube boiler[14]**
Temperature	Can produce saturated steam up to 27 barg (230°C), although most operate below 17 barg (210°C).[15]
Production Capacity	Typical production capacity is up to 27 tonnes of steam per hour, approximately equivalent to 21 MW_{th}.[15] Fire-tube boilers are available in a wide range of sizes, from 0.5 MW_{th} for small applications to a maximum of 25 MW_{th}.[12]
Heat Transfer	Heat is transferred from the flame and hot flue gas, with a flame temperature of up to 1,800 °C, to the tube walls, which heats the water contained in the vessel. An increase in the tube wall thickness, which provides structural strength to withstand the pressure in the boiler, limits the heat transfer rate. This translates to a practical pressure limit of around 27 barg.[15]

Fire-tube boiler	
Lifetime	The boiler shell has a lifetime of 30-40 years, while the lifetime of sub-components such as the burner, electrical control system or fans ranges between 15-20 years.[12]

<table>
<tr><th colspan="2">Water-tube boiler</th></tr>
<tr><td rowspan="2">Description</td><td>In water-tube boilers, water is contained in tubes that are heated by the surrounding hot furnace gases. Because water-tube boilers do not enclose large volumes of water, they offer lower inherent risk and respond more rapidly to load change and heat input. Water-tube boilers are also more efficient than fire-tube boilers, reaching 85% efficiency when equipped with an economiser.[13] Moreover, they can present a higher steam output and can operate at higher pressures.

The market for large water-tube boilers producing superheated steam, typically used for coal-fired power generation, is declining in the UK, as they are being replaced by gas turbines and CHP plants.</td></tr>
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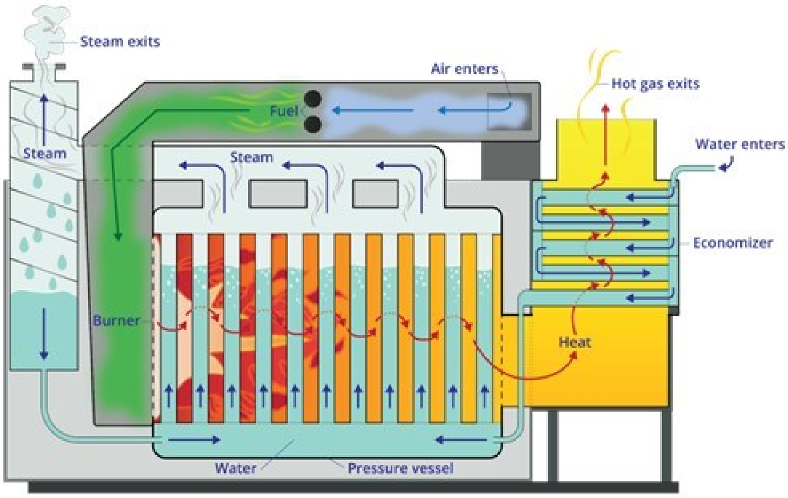


Figure 9: Illustration of a Water-tube boiler[14]

</td></tr>
<tr><td>Temperature</td><td>Can produce superheated steam (up to 550 °C) and operate at pressures up to 160 barg.[16]</td></tr>
<tr><td>Production Capacity</td><td>Production capacity is up to 1,800 tonne steam per hour, approximately equivalent to 1,300 MW_{th}.[16] Typical sizes range between 25 and 500 MW_{th}.</td></tr>
<tr><td>Heat Transfer</td><td>Heat is transferred through the tube walls, heating the water inside the tubes until steam is produced. The radiant heat from the flame is absorbed by finned tubes, whereas the hot gases transfer heat to the tubes by conduction and convection.</td></tr>
<tr><td>Lifetime</td><td>Boiler shell has a lifetime of 30-40 years; lifetime of sub-components such as burner, electrical control system or fans ranges between 15-20 years.[12]</td></tr>
</table>

Electrified alternative – electric steam boiler

The generation of steam can be electrified with heat pumps or with electric steam boilers. Heat pumps can potentially replace fossil-fired boilers for temperatures up to 200 °C and are covered in more detail in Section 4.2.

Electric steam boilers have been commercial for many decades and are technically and commercially mature. They are available at industrial scale, although they are less mature for high-pressure applications and have a smaller capacity than large water-tube boilers. Electric steam boilers are well established in Germany and Scandinavia where electrical grids cope with growing shares of intermittent renewables generations.[17] The increasing proportion of renewable electricity on the power grid increases the need for other assets connected to the power grid to provide necessary frequency control services. Frequency control refers to maintaining the balance between the connected generation and loads on a power grid such that the grid's frequency variations are kept within safe limits required by electrical infrastructure and consumer items. Assets that can quickly ramp up or down their power demand or supply to or from the power grid are recruited to provide frequency response services which require a response within seconds of an imbalance event. Electrode boilers can ramp their power demand (load) from 0-100% of their nominal capacity within 30 seconds.[18]

Two categories of electric steam boilers are commercially available: element boilers and electrode boilers. The simplicity of element boilers may be preferred for smaller applications; electrode boilers are a more appropriate electrification technology for large applications and high temperatures or pressures. It should be noted; however, that the use of electrode boilers for high-pressure steam has less commercial penetration despite having a high TRL of 9.

Element boilers, or electric resistance boilers, use electrical resistance from a heating element to heat or boil water. The heating element is immersed in water contained in the boiler vessel. The flow of current is controlled by a thermostat. They are typically used in smaller applications. The electrical conductivity of water required to maintain effective operation must be kept within a certain level. Typically, this involves treating the water with chemicals or natural minerals. Element boilers are highly efficient (>99%) though this can be affected over time from the build-up of scale or sediment on the heating element.

Element boiler	
Description	An element boiler uses electric current passing through immersive heaters to convert electricity to thermal energy used to heat or boil water.
Temperature	Saturated steam can be produced at a pressure up to 18 barg (210 °C).[19]
Production Capacity	Typically used in smaller applications (up to 5 MW) and are connected at low voltage (e.g., 230 to 690V).[18]
Heat Transfer	An electric current passes through the immersive heaters, and the passage of the current produces heat owing to the resistance of the heaters. The electrical energy, converted to thermal energy, is transferred to water by conduction.
Lifetime	20 years, although it may be lower for resistive components.

In an **electrode boiler**, electric current passes through electrodes immersed in water. The water is heated or boiled from the heat generated through the water's resistance to current flow: power is fed to electrodes, and the current from the electrodes flows directly through the water, heating it in the process. This is in contrast to an element boiler where the resistance of an element provides the heat and current is not conducted through the water itself. Steam accumulates in the upper part of the pressure vessel and is extracted as required. Electrode boilers require high-voltage 3-phase connections, up to 25 kV. They maintain effective operation across a wide range of water conductivities, therefore water treatment is not always necessary. Moreover, they are highly efficient (>99%) and are less prone to scaling and sediment issues compared to element boilers. Electrode boilers have very fast response times and can shift load from 0-100% in approximately 30 seconds.[18]

Electrode boiler	
Description	An electrode boiler uses current flows between electrodes to heat water, with the electric resistance of the water generating the heat directly. Steam accumulates in the upper part of the pressure vessel and is released through a steam valve.
Temperature	Can produce saturated steam at a pressure up to 85 barg (300 °C).[19]
Production Capacity	Capacity of up to 70 MW (110 tonnes steam per hour) connected to high voltage. Multiple single units can be combined in parallel for larger applications.[20]
Heat Transfer	An electric current between electrodes passes through water. Electric energy is converted into heat directly by the resistance of water.
Lifetime	20 years.

Summary of key engineering data metrics – electric boiler

Data Metrics	Gas-fired boiler	Electric boiler	Source*
Efficiency	75% (LHV)	> 99%	18
Capacity	Fire-tube: 25 MW_{th} (27 tph steam) Water-tube: 1000s MW_{th} (1000s tph steam)	Element: 5 MW_e (~ 6.5 tph steam) Electrode: 70 MW_e (110 tph steam)	19,20
Electricity supply requirements	N/A	Element: Single-phase connection, 230 V, 400V, 690V Electrode: Single / three-phase connection, 6-24 kV	19
TRL**	9	9	
CRI **	6	6	
Lifetime	+25 years	+/-20 years	18
Nominal Capex (incl Installation)	Fire-tube: £52k / MW_{th} Water-tube: Not available, replaced by CHPs	Element: £ 130k /MW_{th} Electrode: £ 61k /MW_{th}	18
Fixed O&M	Fire-tube: £1,700 / MW_{th} /yr Water-tube: Not available, replaced by CHPs	Element: £ 931 / MW_{th} / yr Electrode: £ 931 / MW_{th} / yr	18
Year of availability	N/A	2023	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying steam generation

Barriers delaying the deployment of electric boilers in steam generation applications:

Steam generation with electric steam boilers faces some barriers that may limit adoption by industrials. The main barriers are the operational costs, the electric connection requirements, and the lower market penetration for high-pressure steam applications. The first two barriers apply more generally across electrification technologies and are discussed in Section 4.7.

Regarding the **low market penetration of electric boilers for high-pressure applications**:

- While element boilers and electrode boilers are sufficiently mature technologically (TRL 9) and are commercially available, their use for high-pressure steam generation is relatively novel, with limited commercial deployments (of electrode boilers in particular). PARAT, a leading electric boiler manufacturer, offers a high-pressure electrode boiler with a design pressure of 85 barg and 30 MW and market it as the world's first modern high-pressure electrode boiler.[19] Despite this, electrode boilers can comfortably address the low and medium pressure steam that can be produced by a fossil-based fire-tube boiler (27 barg), likely covering a significant proportion of industrial boilers.

Innovation needs for the deployment of electric boilers in steam generation applications:

- **There are no innovations required for the technology to provide steam across most industrial applications**. Industrial electric boilers are well demonstrated at the required scales and are commercially available for most industrial applications. However, further demonstrations of electrode boilers in larger industrial applications may be necessary to increase the confidence in their high-pressure steam capabilities.
- **Documenting technical information around the demonstration of electric boilers in large industrial applications will improve awareness in industry** of the viability of the technology

Drivers accelerating the uptake of electric boilers for steam generation applications:

- **Lower equipment and installation cost**: electric boilers typically present a lower equipment and installation cost than the counterfactual gas-fired boilers (excluding potential capital costs for grid connections – discussed further in section 4.7). This can lead to lower total capital requirements.
- **Higher energy efficiency**: electric steam boilers have a higher energy efficiency (over 99% compared to 80-85% efficiency) than gas-fired equivalents, reducing overall energy consumption.
- **Ability to provide frequency response services**: Large industrial electric boilers have a significant electricity load that can be rapidly ramped making them effective agents for frequency response. The use of electric boilers in this way will likely be dictated by wider regulatory frameworks and economic incentives.

4.2 Paper mill

The UK paper industry is a key contributor to the UK's industrial activities, directly employing 62,000 people and supporting an additional 210,000 jobs in the wider supply chain. The sector has an annual turnover of £12 billion across the following products and services.[21]

- Paper and board products: 3.9 million tonnes
- Corrugated board production: 5.3 billion square meters
- Tissue parent reel production: 738,000 tonnes
- Recovered paper collection: 7.5 million tonnes

These products are made in 47 paper mills across the UK which are responsible for nearly 1.5 $MtCO_2e$ of direct carbon emissions from fuels (excludes scope 2 emissions from electricity purchases).[22] The direct emissions in this sector mainly arise from the production of steam in gas boilers. Approximately 67% of the energy demand in a typical UK paper mill is from the drying process which is powered by steam and electricity (from onsite CHPs and grid imports).[23] The UK paper industry generates more electricity (1.7 TWh) than it imports from the national grid (1.5 TWh). The other fuels consumed in this sector are: natural gas (8.2 TWh); renewables (2.8 TWh – mainly solid biomass); other fossil fuels (0.1 TWh – oils and waste).[22,23]

Overview of paper production mill processes

Papermaking in the UK can generally be divided into the following two steps: stock production – the preparation of the pulp, and the paper machine – the conversion of the pulp into paper or board.

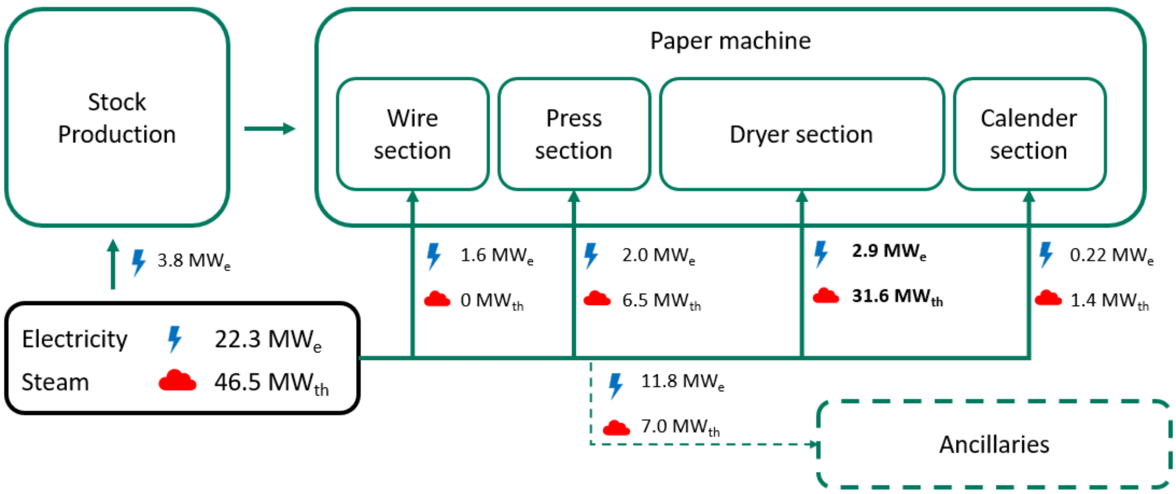


Figure 10: Process diagram and energy balance for a generic paper mill, adapted from Carbon Trust[23] (supported by Table 6 in the appendix)

Stock (pulp) production: A large proportion of pulp in the UK originates from recycled paper. The few sites that use virgin pulp produce it through mechanical refining, wood grinding or through chemical processes.[24] The use of recycled paper necessitates additional cleaning and de-inking steps to remove impurities and produce high-quality paper. These processes are mostly electrically driven.[25,26]

Paper machine: the following sections are used to transform the pulp into paper or board:

- Wire section (web forming): Pulp slurry is sprayed on a flat wire screen moving at high speed through the machine to let the fibres form a paper web. The paper on the web is usually drained to a solids content of 12 – 20%.
- Pressing section: In the pressing section, the paper (supporting on felts between rollers and through vacuum sections) is de-watered to a dryness of 50% solids.

- Drying section: The paper is passed through a series of heated cylinder cans where the paper is further dried to a solids content of 90 – 95%. The cylinder cans are hollowed out and heated by the steam flowing through them and condenses, releasing its latent heat. Much of the heat input to the drying section leaves as hot, wet exhaust air (typically at 80 – 85°C and 140 – 160 g H_2O / kg dry air) which is difficult to reuse.
- Calender section: After the paper machine, the paper passes through a calender consisting of two or more rolls which applies pressure to the paper and produce a smoother, glossier paper product. The paper is subsequently rolled onto a ‘jumbo’ reel where is made ready for any rewinding and other additional processing steps as required.

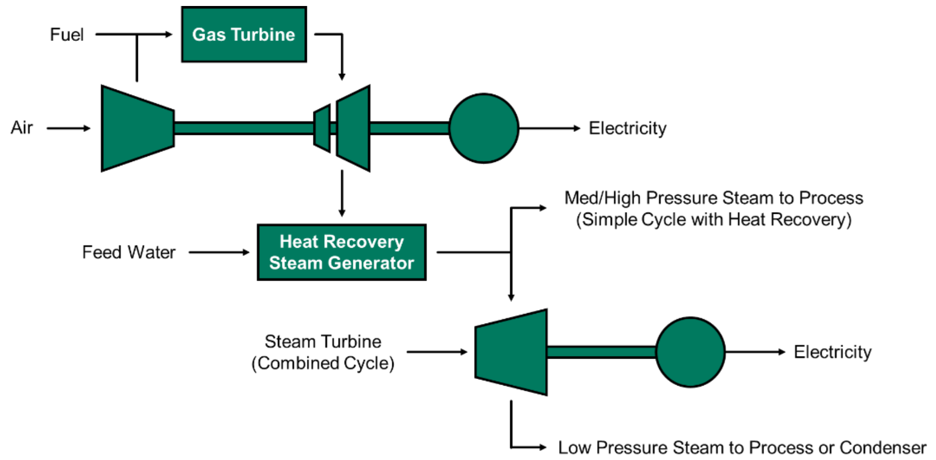
As seen in Figure 10, most of the onsite energy consumption in a paper mill comes from using the paper machine (approximately 67%). The most energy intensive step within the paper machine is the drying section. Furthermore, 85% the thermal energy (heat) consumption in paper mills is used in the paper machine.[23] The paper machine also consumes the biggest proportion of electrical power (roughly 13%).[24] This heat predominantly takes the form of low-pressure steam at roughly 150°C to 180°C, mainly used in the drying section.[24,25] If there is a drying hood in the drying section, the wet air exhaust can be partially recovered through heat exchangers. The steam used in paper mills is predominantly supplied by natural-gas-fuelled combined heat and power (CHP) systems because the typical ratio between steam and electricity demand falls within the optimal operating range of a gas turbine.

Incumbent heating process – combined heat and power (CHP)

A mix of heat generating technologies are used for paper manufacturing in the UK:

- **Gas turbine CHP:** Combusted fuel gases are used to turn a turbine to produce electrical power. The hot exhaust gases (up to 600°C) are passed through a heat recovery steam generator (HRSG) that provides steam to the process. A steam turbine can also be used to extract additional electrical power before being used in the process at reduced pressure.
- **Conventional or Biomass CHP:** natural gas or biomass is burned in a boiler to produce high pressure steam that is routed to a steam or back-pressure turbine to produce electricity and steam for the process.
- **Boilers:** Conventional steam boilers, running on either natural gas or biomass, are still installed in some paper mills with lower steam demands due to the economic constraint of installing a CHP.

The type of technology used on-site depends on the particular split between electricity and steam demand on the paper mill, which varies depending on the product. The operational characteristics of a gas turbine CHP are discussed below.

Combined heat and power (CHP)	
Description	Gas turbines operate by compressing atmospheric air, heating it by fuel combustion and then expanding the exhaust in a power turbine to generate electricity. The energy from the hot exhaust from the turbine, up to 600°C, is recovered in an HRSG, essentially a boiler, to produce high pressure steam which can be used either fully as process steam or used in a steam turbine to produce additional power. If the latter route is used, the resulting turbine exhaust will be low pressure steam which can also be used for process heat as required.  **Figure 11: Illustration of typical gas turbine CHP with HRSG and steam turbine**
Temperature	Paper production mills mainly use steam with temperatures between 150 and 180°C.
Production Capacity	Previous analysis by the Carbon Trust looked at the power stations of UK paper mill (kept anonymous) operating 4 paper machines.[23] The capacity of the site was as follows: Main fuel gas input to the compressor and gas turbine – 51.6 MW Power output from the gas turbine – 9.2 MW_e HP steam from waste recovery boiler – 14 barg, 343°C, ca. 27 MW_{th} Power output from steam turbine – 1.8 MW_e LP steam to plant – 2.2 barg, 150°C, 30 t/h, ca.17 MW_{th}
Heat Transfer	The latent energy of steam condensation is used to transfer heat from within the rotating cylinders of the drying section to the paper rolled out on the cylinder's surface.
Lifetime	The equipment in paper production mills can last up to 10 to 20 years with a major refurbishment during this period.[24]

Electrified alternative – compression heat pumps / MVR

The electrification of paper production mills in the UK can be achieved by electrifying the steam generation process. Steam can be provided by electric boilers or compression heat pumps. Electric boilers were covered extensively in section 4.1. Since paper production mainly relies on low-pressure steam for process heating, these operational requirements are well within the capabilities of electric boilers. Furthermore, there are several electric boiler products available commercially that could be used to replace steam production from paper CHP. The main challenge in implementing electric boilers in paper mills is not due to technological reasons but rather the required electricity infrastructure and the additional grid reinforcement costs.[25] This is a general challenge for the implementation of industrial electrification but is comparatively worse for electric boilers relative to heat pumps due to the significantly higher efficiencies (and thus lower required electrical capacity) achieved by the latter. These challenges, as they pertain to the paper sector, are discussed more broadly in section 5.2. A joint paper by the European Heat Pump Association (EHPA) and the Confederation of the European Paper Industries (CEPI) has described the papermaking process as "ideally positioned to use heat pumps". This section will therefore focus on steam generation from high temperature industrial heat pumps.

High temperature heat pumps (HTHP) have traditionally been used to provide heating up to 90°C (mainly to heat water for space heating). However, recent developments in the technology have allowed the technical operating envelope to increase to up to 200°C.[27] The difference between the temperature of the heat source and the delivery temperature (also known as temperature lift) is a crucial design parameter affecting the coefficient of performance (COP) of a heat pump. The heat pump COP decreases exponentially as the temperature lift increase.[28] There is thus a trade-off between the designed temperature lift and the achievable COP. For commercial HTHPs with supply temperatures above 100°C, the achievable COP decreases exponentially from 5.2 to 2.4 as the temperature lift increases from 30°C to 80°C.[29]

As discussed in section 2.1, a heat pump transfers energy from a heat source to a heat sink, the application. The heat source can come from ambient air, water or other liquids, ground heat, or waste process heat. The advantage of using waste heat for industrial applications is that the source temperature is not affected by external weather conditions unlike using ambient air. Furthermore, the temperature of the waste heat available on many industrial sites is often higher than other heat sources, allowing for a smaller temperature lift and thus a higher COP. **The main source of waste heat on a paper mill is from the wet exhaust air leaving the dryer section with a dew point of 25°C to 74°C.**[25] The amount of heat that can be recovered depends on the dew point temperature of the waste heat. Many paper mills deploy some form of heat integration measures to recover some of this heat, for example, to preheat the ventilation air used in the dryer or for heating process water. After capitalising on the available opportunities for heat integration, the remaining waste heat is usually dissipated into the atmosphere at 30°C to 40°C.[25] Herein lies the opportunity for HTHPs to be used in recovering this heat and producing the required process steam for the paper mill.[25]

There are over 20 industrial HTHP products on the market today with a high TRL of 8-9. Some manufactures are developing technologies which claim to have a maximum heating capacity of 70 MW_{th} and a maximum temperature supply of up to 280°C.[29,30] Despite the high technological development of HTHP, there has not been substantial roll-out in industrial steam applications due to the current MW_{th} scales (< 5MW_{th}) that are commercially available compared to the requirement.[30]

Commercially available HTHPs can be used to deliver low pressure steam at temperatures narrowly exceeding boiling point (roughly 120°C).[1] Mechanical vapor recompression (MVR) can be used to provide the required heat 'top up' to reach the steam requirements (150°C – 180°C, up to 10 barg) of the paper dryer.[1,25] MVR is an extension of a heat pump system that has traditionally been used for low temperature evaporation processes that need a small temperature lift of 15°C or less.[1] The basic operating principal centres around using multiple compression stages to lift the temperature and pressure of a vapour stream to be used elsewhere in a process. The technology can deliver temperatures up to 250°C but is predominantly used for applications below 100°C.[1] This technology boasts a very high coefficient of performance (COP) of up to 10, for a 15°C temperature lift. Furthermore, MVR technology has been deployed across many industrial applications for processes such as black liquor evaporation in wood pulping, sewage sludge drying and milk evaporation before drying, amongst others. In Sweden, MVR technology has been used to recycle the steam evaporated from the superheated steam dryer (used to dry wet pulp). The overall COP of this demonstration was over 4.7 and delivered 11.2 MW_{th} of heat at temperature of 200°C (saturated steam).[31] It is important to note that MVRs are not capable of generating steam from water, rather they should be seen as a technology that significantly improves the heat integration on an industrial site and therefore reduces the thermal energy demand and thus the associated CO_2 emissions. There have been recent developments in design concepts that integrate the principles of HTHP and MVR to deliver supply temperatures above 100°C. The EHPA and CEPI collaboration has proposed the following concept for integrating heat pump technology into the papermaking process (Figure 12). In this design concept, make up steam can be added to ensure pressure control in the heating cylinders. This steam could be provided by conventional steam boilers or electric boilers.

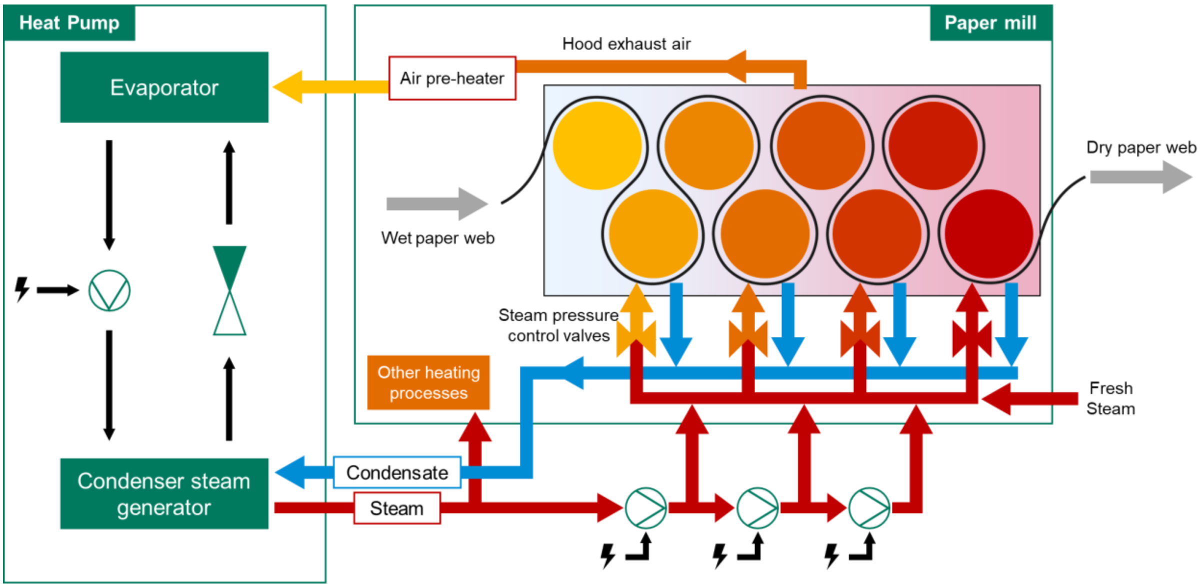


Figure 12: Illustration of a high-temperature heat pump (HTHP) and mechanical vapor recompression (MVR) concept for producing steam for the dryer in papermaking (adapted from CEPI & EHPA report).[27]

High Temperature Heat Pump[30]	
Description	Electricity is used to move thermal energy from a heat source to an application at a higher temperature through a compression /expansion cycle.
Temperature	The maximum temperature for an industrial HTHP demonstration is roughly 120°C from a heat source at 60°C
Production Capacity	Industrial HTHPs (heat pump without MVR) specifically for steam supply have only been demonstrated to a heat supply capacity of 1.9 MW and a COP of 3.5 (as reported by annex 58 of the IEA's Technology Collaboration Programme on Heat Pump Technologies).[32] In this application, 5 heat pump units are needed to achieve this capacity. However, manufactures such as Siemens Energy have developed HTHP products that can reach 30 MW_{th} for low-pressure steam (<3.5 bar) and 45 MW_{th}. for medium pressure steam (<8.3 bar) applications.
Heat Transfer	Heat pump cycles can be designed to produce steam from a waste heat temperature source, especially when integrated with MVR.
Lifetime	Heat pumps can have a system lifetime of between 15 – 20 years.[33]

Mechanical Vapour Recompression (MVR)[28,30]	
Description	Electricity is used to drive the mechanical compression of a vapour stream (which could be produced by a HTHP) in multiple stages in order to lift its temperature and pressure.
Temperature	A Swedish case study for MVR use in pulp drying shows a heat source of low-pressure steam at 2.2 barg and 133°C being lifted to 15 barg and 240°C.[31]
Production Capacity	The Swedish case study for MVR use in pulp drying shows a maximum heat supply capacity of 11.2 MW_{th} with a COP of 4.2 (but with potential for a COP > 4.7)
Heat Transfer	In paper mills, MVR can either be used to recompress an existing vapour stream onsite or used alongside a HTHP to generate steam. This application is however still being explored and has no existing demonstration cases.
Lifetime	MVRs have a comparable operating lifetime to traditional CHPs with roughly 20 years of useful life.

Summary of key engineering data – compression heat pumps

Data Metrics	Combined Heat and Power	HTHP / MVR	Source*
Efficiency	Electrical: 20 – 30% Thermal: 40 – 60%	HTHP COP: 3 – 7 MVR: up to 10	1
Capacity	LP steam supply around 20 MW_{th}	Current largest demonstration is < 2 MWth for steam generation; however, manufacturers claim to have designs capable of 10 – 45 MW_{th} (larger systems are TRL 7 - 8)	29,30
Electricity supply requirements	N/A	Single/three-phase connection, 6-24 kV	
TRL**	9	HTHPs: 7 – 9, MVR: 7 - 9	2
CRI **	6	2 – 4	
Lifetime	+ 25 years	15 – 25 years	34
Nominal Capex (incl Installation)	Combined cycle gas turbine (CCGT): £ 720k / MW_e	£ 200k – 1,200k / MW_{th} (capex per MW decreases with increasing unit capacity)	18,35
Fixed O&M	£ 25 k / MW_e / yr	£ 1.7k - £ 63k / MW_{th} / yr	18,34
Year of Availability		2025 – 2030	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

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Specific barriers, innovation needs and drivers for electrifying paper production

Barriers delaying the deployment of high temperature heat pump technologies in papermaking:

- **Thermal output capacity:** HTHP technology has not currently been demonstrated in an industrial application at the required operating scales for paper production mills (10s of MW_{th}) although many technology developers claim to have systems at this scale. Moreover, these projects often require several heat pumps units to cumulatively achieve heat supply at the MW_{th} scale. Therefore, the physical footprint required by heat pumps, at their current capabilities, may be impractical to sites that are space constrained. There are some technology developers like Siemens Energy that have developed a low-pressure steam heat pump system with a thermal capacity of 30 MW_{th} per unit (including 4 compression stages). This would meet the steam demands of most paper sites in the UK; however, at the time of writing, there are no demonstrations of this system in a specific industrial application.[36]
- **Waste heat source:** The wet air exhaust from the drying section of the paper machine is the most likely heat source for the HTHP application. The dew point temperature of this exhaust varies significantly (25°C to 74°C) depending on the particular site and paper product. It is likely that the existing heat recovery opportunities on a given site will be prioritised before the waste heat stream is used for the HTHP. This implies that the heat source temperature may be significantly lower than the exhaust temperature. This therefore increases the temperature lift required to reach to application temperature of 150°C and thus reduces the COP achieved by the system.
- **Refrigerants:** Heat pumps that use waste heat as a temperature source are dependent upon the use of refrigerants circulating in a closed loop. The main refrigerant classes (chlorofluorocarbons – CFCs) have largely been phased out due to their global warming potential (GWP). The challenge facing the heat pump industry is that this leaves relatively few refrigerants available that are capable of achieving the temperatures required for steam generation applications. Numerous manufactures are exploring the use of natural refrigerants such as ammonia, propane or carbon dioxide, all of which have a relatively low global warming potential (GWP of 0, 3 and 1, respectively).[1]
- **New power supply:** Replacing CHP steam generation with heat pumps / MVR comes with the additional challenge of securing new electricity supply to replace the power supplied by the gas and steam turbines. Since the UK paper production industry cumulatively export about 0.2 TWh_e to the national grid, this implies that replacing the CHP is also a loss of a revenue stream for some paper mills.[22] Furthermore, importing electricity from the grid significantly increases the onsite energy costs since the paper mill would have to pay the additional charges over the marginal cost of power generation (i.e., transmission and distribution charges, taxes, etc.).

Innovation needs for the deployment of high temperature heat pump technologies in papermaking:

- **To promote significant uptake of heat pumps in the paper sector, heat pump and compression systems need to be standardised and fit for purpose.** Many technology developers have system designs with the appropriate performance for paper, but few projects have committed to deploy a heat pump system at scale in an industrial setting. Many paper sites have steam requirements with very similar temperatures and pressures. Heat pump providers can capitalise on this by developing a heat pump and compression system that is optimised to the specific requirements of the paper industry. This would provide more reassurance for plant operators and simplify the process of integrating the system into the existing site.

- **Finding refrigerants that achieve optimal cycle characteristics for an application is a challenge to the application of high temperature heat pumps across all industries, particularly where high temperature lifts and steam generation are required.** While natural refrigerants with the required characteristics have been identified, finding refrigerants with improved characteristics which can optimise the heat pump's cycle is an area of active development. Increasingly, sophisticated computer programs and artificial neural networks are being utilised to identify suitable blends of existing refrigerants from databases of refrigerant properties to achieve optimal performance for a given application.
- **Enrich the knowledge base of the site-specific heat requirements across the UK paper sector and map this against the appropriate HTHP and MVR technologies that can be installed today**. This would involve significant engagement with the Confederation of Paper Industries (CPI) and the extensive list of European heat pump technology suppliers identified by the IEA Technology Collaboration Programme (TCP) for heat pump technology.[30] Despite some of the technical challenges of deploying HTHPs and MVR in paper mills, there are many commercially available products with suitable performance. By clearly mapping suitable products, the process of technology adoption becomes clear and simple for sites exploring their abatement options encouraging uptake.
- **Prioritise near-term opportunities (2 – 4 years) for pilot and demonstration projects to catalyse the required learnings for widespread deployment**. This enables the paper sector to increase the necessary skills and experience needed to implement heat pump and MVR technologies. Furthermore, the sector will gain more transparency in the level of process disruption and redesign required by deploying these technologies and thus share these findings with other sectors for which heat pumps may also be used. These pilots will also inform areas of further technological development for heat pump and MVR system manufactures, leading to further demonstrations in the medium-term (5 – 8 years) as they improve the capabilities and process suitability of their technologies.

Drivers for the deployment of high temperature heat pump technologies in papermaking:

- **Heat pumps have the opportunity to provide deep decarbonisation in the paper sector.** The majority of emissions in the sector arise from drying processes which can be completely abated with high-temperature heat pumps producing low pressure steam.
- **Paper production has an inherent waste heat source that makes heat pumps highly suitable and energy efficient**. The capabilities of heat pumps exceed the temperature and pressure demands of the steam required meaning that no new innovations are required to capitalise on this high efficiency.
- **The high energy efficiency of heat pumps could offer significant operational savings to paper sites relative to alternative abatement options.** Commercially available heat pumps are able to deliver at least twice as much thermal energy relative to the electrical energy supplied to the system (an effective efficiency >200%). This reduces their electricity demand from the grid relative to electric boilers which typically have efficiencies of ~99%. The electricity demand for producing heat using heat pumps is significantly lower than if electricity is used to produce hydrogen which is subsequently combusted.

4.3 Olefins

The UK chemicals sector is highly diversified in chemical processes and the products it produces. There are more than 2500 enterprises employing roughly 106,000 employees with an annual turnover of around £32 billion.[37] The chemical sector could roughly be divided into the following subsectors: organic basic chemicals (petrochemicals); inorganic basic chemicals; plastics and polymers; and other chemicals. The organic basic chemicals subsector mainly includes the production of olefins with other associated intermediates.[37]

Olefins are a class of large volume organic chemicals (LVOCs), consisting of alkenes (double-bonded) hydrocarbons. Since there is a wide range of chemicals under this classification, the specific industrial production processes used differs between sites dependent on the portfolio of chemicals produced. Ethylene and propylene are two of the largest volume chemicals produced globally. The production of olefins accounts for over 70% of all organic chemical production and accounts for roughly 25% of all direct combustion emissions from the chemicals sector.[37,38] Approximately 40% of chemical sector emissions are the result of electricity generation, mainly used to power material transfer operations like pumps, compressors, pipe cooling, conveyors and fans.[37]

There are currently four operational olefin production sites in the UK, including: the ExxonMobil Fife ethylene plant; the INEOS chemical site in Grangemouth; the SABIC 'Olefins 6' plant in Wilton; and the small LyondellBasell polyolefins site in Carrington. The reported emissions from olefins production sites in the UK (2.8 $MtCO_2e$) is the fourth largest contributor to total industrial emissions, according to the 2021 NAEI dataset. The manufacture of petrochemicals predominantly uses approximately 11 TWh of natural gas, 0.35 TWh of coal and smaller amounts of petroleum gases and gas oils to fire the combustion processes.[39]

Overview of olefins sector processes

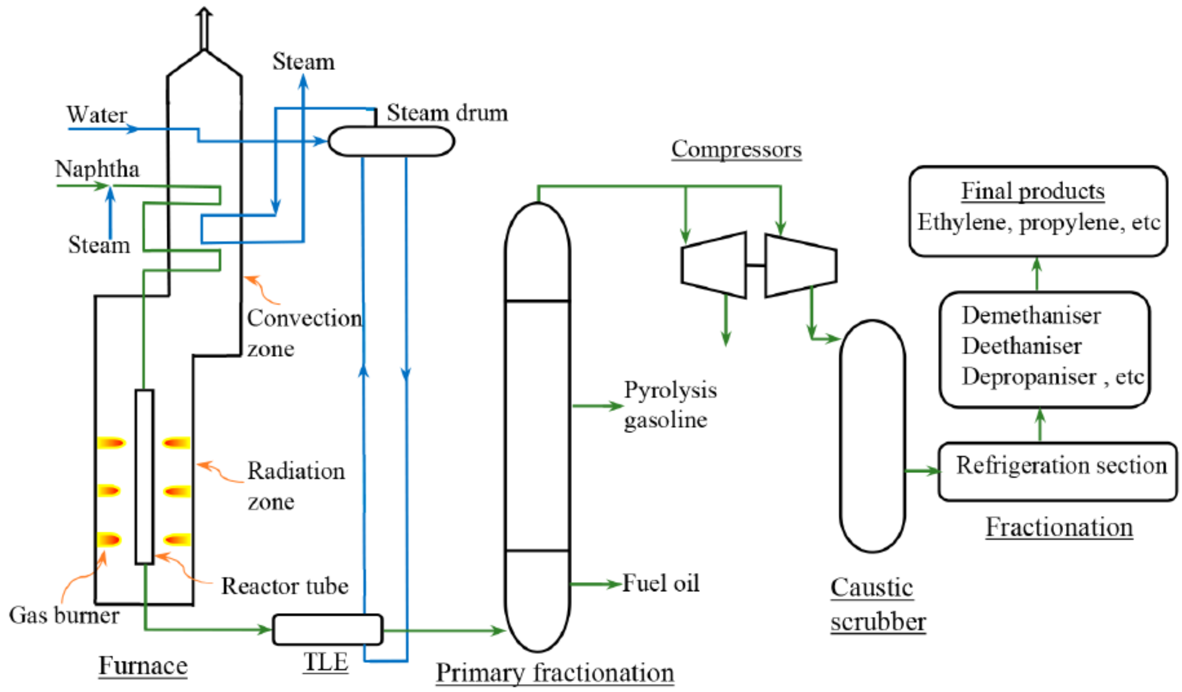


Figure 13: Diagram of a typical Naphtha cracker plant[40], described in the text

The steam cracking processes can generally be divided into the following components (shown Figure 13):[40,41]

- **Feedstock preparation and pyrolysis furnace:** olefins can be produced from a variety of feedstocks originating from the products of crude oil refining (e.g., LPG, Naphtha, natural gas condensates etc). In most cases, these feedstocks are often transported directly from the oil refineries to olefin plants via pipeline and stored onsite in tanks. Pyrolysis is a high temperature thermal process in which the feedstock hydrocarbons are chemically decomposed into smaller alkene chains.

The naphtha feedstock is firstly preheated to approximately 600°C before passing through the radiant section of the cracker. This preheating is done by mixing the feedstock with superheated steam. The radiant section of the cracking furnace is lined with gas burners to provide radiative heat in a uniform distribution to the cracking coils. The cracking reaction typically occurs in cracking coils in the radiative section at roughly 850°C. To reach these high temperatures, external heating is provided by the combustion of natural gas and/or recycled fuel gases.

In the convective section of the furnace, the hot cracked gases (at 850°C) are rapidly cooled to prevent the thermal degradation of some highly reactive products. This occurs by heating up boiler feedwater to produce high pressure steam (HPS) in transfer line heat exchangers (TLEs). The high-pressure steam (HPS) produced as a result is used to drive the turbines of the downstream compressors. Furthermore, in the convection section, heat from the combustion flue gases is recovered to raise the HPS to superheated steam which is used to heat the naphtha feedstock to the required temperature. The hydrocarbon feedstock is also diluted with low-pressure steam (LPS) to reduce its vapor pressure, thereby preventing coke formation in the furnace tubes.

- **Primary fractionation and compression:** After passing through the TLEs, the cracked gases are further cooled in a quench tower to 200°C, partially condensing the gas stream. The condensate from this step typically contains heavy condensate (fuel oil), which are separated from the cracked gas, and can be sold as valuable product. The cracked gas undergoes several steam-driven compression, intermediate cooling, and separation stages to remove additional heavy hydrocarbons (pyrolysis gasoline) as well as water from the gas stream to prevent ice formation in the downstream cooling and distillation processes.
- **Product separation:** a cryogenic refrigeration unit can be used to cool the dried gases to a temperature of negative 165°C at which almost all hydrocarbons are condensed. The gases that rise to the top of this unit process are mainly hydrogen, methane, and carbon monoxide. This stream can be further separated to produce pure hydrogen for various catalytic reactions, or a methane rich stream for fuel use in the steam cracker. The heavy condensate that settles at the bottom of the unit undergoes several distillation and separation processes which ultimately produce the main products of the site.

Pyrolysis steam cracking comprises roughly 85% of the useful energy demand for combustion heating on an olefin plant and is thus the investigation focus for future electrification opportunities. Through the cooling required by cracked gas to reach the various separation conditions, heat is provided to other processes such as steam generation which is the other main combustion heating process onsite. The electrification opportunities for steam generation have already been discussed earlier in the report.

Incumbent heating technology – pyrolysis steam cracker furnace

Pyrolysis Steam Cracker Furnace	
Description	Cracking coils provide a confined space for the hydrocarbon feed and steam mixture to be heated in the presence of a catalyst leading to the desired cracking reactions. Burners directly heat the metal coils in a radiant firebox – uniform heating limits coking within the coils. Self-produced fuel gas is used to fire the burners which balances the production slate. Cracked gas then moves through the transfer-line heat exchangers in the convection zone where it heats

Pyrolysis Steam Cracker Furnace	
	an incoming stream of boiler feed water, cooling the cracked products to prevent degradation and producing superheated steam that drives the compressor.

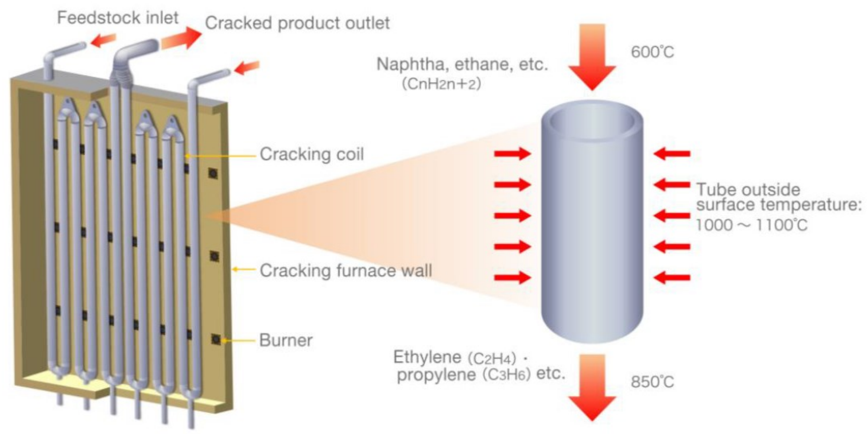


Figure 14: Schematic of a naphtha cracking furnace[42]

Temperature	Furnace burners raise the temperature of the tubes to the required levels (typically between 750°C and 950°C) at which point the reaction occurs.
Production Capacity	Large pyrolysis crackers produce several hundred thousand to over a million metric tonnes of olefins per year (10s – 100s MW_{th}). Conventional steam crackers show an ethylene yield of roughly 31%.[40]
Heat Transfer	The temperature and pressure in the radiant box must be accurately controlled to maintain optimal cracking conditions meaning that a precise temperature distribution is required. Heat fluxes higher than 30 kW/m^2 are required at the reactor coil to promote the cracking reactions.[40]
Lifetime	Pyrolysis cracker furnaces can last for several decades (20+ years)

Electrified alternative – electric cracker furnace

Technologies for the electrification of hydrocarbon cracking reactors have been under development for over a century, with over 30 patents in the last two decades.[40] **Arc/plasma heating and resistive** technologies have had the most patents because they are seen to be easier to implement and scale up [40]. More recently, **shockwave technology** has been applied in Coolbrook's rotor dynamic reactor (RDR) specifically for the cracking of hydrocarbons.[43]

A typical pyrolysis cracker is sized for roughly 100 MW_{th} input, of which, about 50% of the thermal input to a conventional cracker is lost to the production of flue gases. Since electric cracking does not use combustion processes for heat, the required scale of an electric cracking furnace of the same output can be roughly 50 MW_e.

Electric arc crackers: In the 1920s and 1930s, there were two operational electric arc/plasma crackers operating at a 10 MW scale, however, there are currently no commercial crackers deployed using any of the technologies listed above.[40] According to industry experts, this is because the cracking reactions in the furnace tubes are very dependent on the reaction temperature profile to achieve the high product selectivity required.

Resistance heating: Several literature sources have concluded that, out of the available electric furnace technologies, resistance heating is a more likely replacement for conventional gas-fired furnaces because of its simplicity and efficiency.[3,4] However, there are currently no commercial products for electric resistance steam crackers that can fully replace a conventional steam cracker.

Implementing resistive heating elements in conventional steam cracking furnaces, in a way that minimises the amount of modifications to the furnace, has been proposed in literature.[40,41] In a conventional steam cracker, the existing tubes could be heated by electric resistance by either placing heating elements in direct contact with the tube or using the resistance of the tube itself to provide heat by passing a high voltage current through it. A potentially more convenient approach to implementing resistive heating would be to retrofit the existing gas burners that line the furnace wall with resistive heating modules.

- **Electrically heated furnace tubes:** Laboratory scale research by Wiseman *et al.*, showed through experimental and computational data that electrifying the reactor in this way achieves a more uniform supply of heat to the process while ensuring more efficient use of the reactor volume (see Figure 15).[44]
- **Retrofitting the furnace walls:** This approach is potentially more likely to maintain the radiative mode of heat transfer in this section of the cracker.[40] Furthermore, this approach allows for the possibility of partially electrifying the existing furnaces, enabling the more probable stepwise electrification of cracker furnaces.[45] Some furnace product suppliers have claimed that these heating modules can provide a heat flux of over 80 kW/m^2 for a furnace temperature of 900°C, more than adequate for cracking reactions.[46]

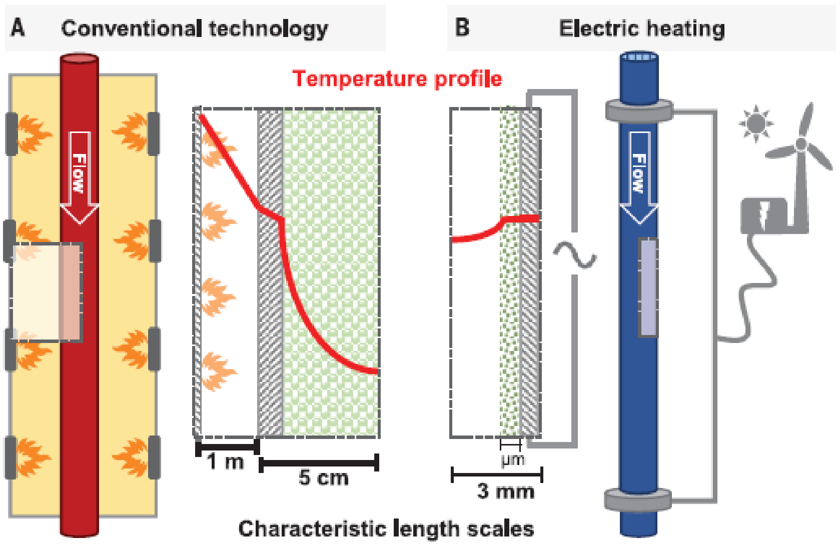


Figure 15: Illustration of a temperature profile for conventional gas-fired heating compared to electric resistive heating[44]

Shock wave technology: This technology has been successfully demonstrated at bench scale (TRL 4) for cracking hydrocarbons for ethylene production using Coolbrook's patented rotor dynamic reactor (RDR). Electricity is used to power a shaft of rotating blades which agitates gaseous hydrocarbons to supersonic speeds and the resulting kinetic energy is converted to the required high temperature heat. Coolbrook's simulation of a full-scale RDR cracker has shown a 25% increase in ethylene yield and a 20% decrease in the physical footprint of cracker compared to a conventional steam cracker for the same product.[43] They now intend to validate these results through their RDR pilot plant (TRL 5) at the Brightlands Chemelot Campus in Geelen (Netherlands) which is designed to produce 400 kg of naphtha per hour (or roughly 3000 tonnes per year).[47] This is at least two orders of magnitude smaller than conventional steam crackers which process several hundred thousand tonnes of naphtha per year.

There are several consortiums currently developing demonstrations projects for electric crackers which hope to provide further insights on the implications of electrifying steam crackers (Shell & Dow;

VoltaChem; BASF & SABIC; as well as the Lyondellbasell, Technip and CPChem consortium).[48,49] Several literature reports suggest that resistance furnaces have a potential role to play in steam cracker electrification.[2,41] There are no commercial electric cracking products or full design concepts for crackers that can fully replace a conventional steam cracker. The BASF and SABIC demonstration project in Ludwigshafen, Germany, will be testing two different electric heating concepts in parallel, both of which are based on resistive heating principles. The first concept directly applies an electric current to the furnace tubes inside the reactor, while the second utilises restive heating elements around the tube. This project is design to process approximately 4 tons of hydrocarbons per hour with a cracker electrical capacity of 6 MW_e. This is roughly 50 times smaller than the complete cracking capacity of the site which can process roughly 2 million tons annually (about 200 tons per hour).[50] The table below summarises the suitability of the three concepts of implementing resistance heating for steam cracker furnaces. These concepts could either be applied in a greenfield implementation of an electric cracker or a retrofit of an existing conventional steam cracker.[40]

Electric resistance Steam Cracker Furnace - Retrofit	
Description	**Retrofitting the furnace wall:** resistive heating elements can be used to replace the existing gas burners in the furnace. These heating elements will be fastened onto the inner furnace lining of the radiant box and provide radiant heat to the furnace tubes. **Indirect resistive heated furnace tubes:** resistive heating elements are placed around the furnace coils.
Temperature	Resistive heating modules have been shown to reach temperatures above 1000°C.
Production Capacity	The BASF and SABIC demonstration project will be processing roughly 4 tons of hydrocarbons per hour with an electrical capacity of 6 MW_e.
Heat Transfer	For furnace wall retrofits, there are commercial resistive heating products capable of producing a heating power flux of 80 kW/m^2 for a furnace temperature of 900°C.[40]
Lifetime	Several reports propose that electric crackers will potentially have a lifetime of 20 years.

Summary of key engineering data - electric cracker

Data Metrics	Gas-fired steam cracker	Electric resistance cracker (indirect resistive heating)	Source*
Efficiency	75% (LHV) – typical natural gas combustion	>99%	41,51
Capacity	10s – 100s MW_{th} (1 – 1000s kt olefins per year)	6 MW_e (Up to 35 kt olefins per year)	41,51
Electricity supply requirements	N/A	Three-phase connection, 6-24 kV	
TRL**	9	6	52
CRI **	6	1	
Lifetime	+20 years	+/-20 years	51
Nominal Capex (incl Installation)	~ £ 360 k / kt olefins / yr (34% ethylene yield)	Capex: £ 760k - £ 870k / kt ethylene per year	51

Data Metrics	Gas-fired steam cracker	Electric resistance cracker (indirect resistive heating)	Source*
Fixed O&M	£ 17 k / kt olefins / yr (34% ethylene yield)	£ 12k – £ 18k/yr (based on a 10 MW_e furnace)	51
Year of Availability		2030 – 2035	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying olefins heating

Barriers delaying the deployment of electric crackers in olefins production:

Although electric heating modules are sufficiently developed technologically, the impact of their use in retrofitting conventional steam crackers is not yet understood. Similarly, electric technologies for fully replacing the conventional steam cracker are very early in their technological development (TRL 4 – 6). The main challenges facing these two implementation strategies **are the design of the electric cracking reactor** as well as **the wider implications that electrification has on the heat integration of the plant.**

- The **impact of electric cracking on final product yield and quality is not yet understood.** Electric crackers must be designed to maintain or exceed the required product yields and selectivity currently achieved by conventional steam crackers. Maintaining the correct yield requires a precise control over the process temperature, something that is well understood for the incumbent combustion systems. Electrification is excellent at providing precise temperature control; however, awareness around calibrating these systems amongst existing site engineers may be low. Testing in pilot projects will improve understanding around how to best arrange and operate the electric heating system so that the desired chemical reactions are precisely controlled.
- **The electrification of the steam cracker creates a surplus of flue gases onsite.** Like oil refining activities, olefin production involves significant use of the recycled exhaust gases from the steam cracker to fuel other combustion heating processes onsite (such as feedstock preheating). Since the fuel gas is an intrinsic by-product of the steam cracking process, a surplus of fuel gas is created onsite. Sustainable alternatives for this surplus fuel must be found for the electrification of this process to be an appropriate decarbonisation pathway.
- **Electrifying the steam cracking units and the steam driven compressors may disrupt the complex steam balance used on olefins sites and require investments in new steam supply.** The production process for olefins usually requires at least four compressors (for cracked gas, methane, ethylene, and propylene) which are driven by steam turbines. These turbines are powered by the various grades of steam produced at the steam cracker from either the hot cracked gases of the radiant section of the cracker or the flue gases of the convective section. The output from these turbines is low pressure steam that is either used for process heating or to run other steam turbines. These compression systems can already be electrified with the mature and more efficient electric compressors of today, which are readily available. However, electrifying the steam crackers and compressors will disrupt the balance of supply of high/medium pressure steam since there will be no superheated steam production from the lack of flue gas from the cracker. This will mean that the site will need to invest in steam imports or new electric boilers to make up for the shortfall.
- **UK olefin production sites are mainly located within industrial clusters.** The UK Government CCUS Cluster Sequencing programme may act as an incentive for olefin sites

within industrial clusters to preferentially deploy carbon capture or fuel-switch to hydrogen, as an alternative to electrification. This is both due to the ability to access shared transport and storage infrastructure, and the potential opportunity for subsidies via the UK Governments CCUS Business Models.[53]

Innovation needs for the deployment of electric crackers in olefins production:

- **Further research and development is required to resolve technical uncertainties around the relevant electric cracking designs** that can achieve the product yield and quality required by industry. For indirect heating with resistive elements (of either the furnace walls or furnace tubes), R&D should be focussed on how to incorporate these elements into furnace designs to achieve the required heat transfer rate and heat distribution throughout the cracking coils for cracking reactions to occur. Heating elements are commercially available with the required heat flux and temperature control parameters; however, the application and arrangement of these elements for optimised performance needs to be investigated.
- **Monitoring of the results of current first-of-a-kind (FOAK) consortium projects is required to establish further areas of technological development.** As mentioned earlier, there are several demonstrations underway for ethylene production through electric cracker technologies. The most developed demonstration project seems to be Coolbrook's RotoDyamic Reactor (RDR) at the Brightlands Chemelot campus in Netherlands, which expects industrial deployments by 2024.[43] Engaging with developers and monitoring results of these projects will provide learnings that could be transferred to the UK and steer future developments.
- **Further R&D is needed to understand the wider process integration implications of deploying electric crackers**. **Partial electrification of the steam cracker has been proposed** to reduce the impact that full electrification of the cracker has on the site balance of fuel gases and steam supply. This would enable a gradual electrification of the olefins production process.

Drivers for the deployment of electric crackers in olefins production:

- **A decrease in the formation of contaminants within the fuel system can be achieved by electrifying the heating process**. Combustion systems can result in the deposition of coke and other contaminants on the interior surface of the fuel pipes due to the presence of hot spots which reduces the reactor efficiency[50]. Coking can also lead to system failures and downtime which is highly costly to a refinery.
- **Increased temperature control can be achieved with electrified systems which can respond rapidly to system changes to vary their heat output**. The ability to quickly respond to system changes and maintain stability is highly valued on chemicals sites, bringing improvements in productivity and safety.
- **Electrified heaters can eliminate combustion emissions from an electric cracker completely**. This can lower a chemicals site's dependence on other abatement options such as carbon capture and low carbon fuels, both of which bring their own application challenges in the context of a refinery's process flow.
- **The increased temperature control of the electrified reactor can lead to an improvement in reaction selectivity** meaning that less feedstock is required to produce a quantity of desired products. Since the price of naphtha dominates the operating costs of olefins production, increases in selectivity have a significant decrease on production costs. This may mean that the use of an electrified system lowers the operational costs of cracking despite electricity being more expensive than natural gas.

4.4 Integrated cement kiln

The UK produces roughly three quarters of the cement it requires, with 9 million tonnes of domestic production.[54] Six cement manufacturers operate across 10 sites with integrated kilns, providing employment to many in rural locations.

The cement industry is highly energy intensive and cement plants consume large quantities of coal, waste derived fuels and electricity. Alongside emissions from combustion, the cement industry is responsible for the production of a significant quantity of process emissions arising from chemical reactions in the cement production process. As an industry, cement production in the UK results in 5.8 $MtCO_2$/year.

Overview of cement sector processes

The main purpose of cement is to act as a hydraulic binder for sand particles and aggregates to give strength to concrete, one of the most versatile and widely used materials in the construction industry. Cement can also be used to produce mortar when it is combined with water, lime and sand. While there are a plethora of different cement types and sub-types, the most common general cement product is called Portland Cement. The main ingredient of Portland Cement is clinker (up to 95% content) while the other ingredients are gypsum and fine limestone. Despite the many categories and strength classes of cement, the main production steps are the same at any site.

Figure 16: Schematic of common production steps in cement production as described below

- **Crushing and raw meal grinding**; cement plants are often situated near natural deposits of minerals containing calcium carbonate. These are combined with materials containing alumina (Al_2O_3), silica (SiO_2) and iron (Fe) and then crushed and ground to provide a mix known as 'raw meal' with desirable chemical and physical properties for cement production.
- **Precalcining**; on many plants, the powdered raw meal is fed into the top of a preheating tower. As the meal passes down through the units of the tower it moves through multiple cyclone preheaters which utilise hot flue gases from the plant's kiln to heat up the powder in suspension, improving the efficiency of reactions in subsequent steps. Calcination describes the decomposition of calcium carbonate (limestone) into calcium oxide (lime) and this reaction begins in a combustion chamber called a precalciner. After the raw meal has passed down through the preheating units it enters the precalciner where it is heated by the kiln flame as well as its own burner system. The combustion air for most precalciners by-passes the kiln to avoid blowing powdery feed out the back of the kiln. This enables the degree of calcination of feed entering the kiln to reach as high as 90-95%. Any higher than this and clinker begins to form in the precalciner which must be avoided. During the decomposition reaction, CO_2 is released as a by-product of the reaction. Combined with the significant dedicated fuel use for this unit, the precalciner is the source of up to 85% of emissions on a cement plant.
- **Clinker production**; the precalciner passes meal into the top end of a rotary kiln. Rotary kilns are heated by direct-fired gas burners which raise the meal to extremely high temperatures. The rotary motion of the kiln drum continuously moves the meal further down the kiln to increasingly high temperatures. While calcination is one step in the production of clinker, the final chemical and physical changes require intense heat achieved at the peak temperature of the kiln. The meal melts then re-freezes exothermically forming clinker nodules.
- **Cooling, grinding and blending**; a grate cooler is used to cool hot clinker by passing air over it as it exits the rotary kiln. The air is heated and can subsequently be used as an air

intake for the combustion system. The clinker is then ground in a mill to produce a fine powder which can be blended with supplementary cementitious materials and additives on-site or at a dedicated blending site.

Incumbent heating technology – rotary cement kiln and precalciner

Over 60% of a cement plant's emissions arise from process emissions in the calcination process. Additionally, the intense heat required for calcination and clinker production results in significant combustion emissions. The split of these combustion and process emissions between the precalciner and rotary kiln depends on the individual plant balance; however, the precalciner is typically the most emissions intensive unit in the system. Combined, the precalciner and rotary kiln provide the most substantial opportunity for emissions reduction.

Decarbonising the heat source for the precalciner and rotary kiln does not eliminate the process emissions from calcination; however, it can result in lower volumes of flue gas with a higher purity of CO_2. By electrifying heating processes, combustion gases are removed from the flue gas leaving a high purity stream of process emissions. Consequently, electric heating technologies can complement carbon capture technologies at cement sites by reducing the volumes of CO_2 that need to be captured and increasing the concentration of CO_2 in the flue gas (by eliminating low purity combustion gases).

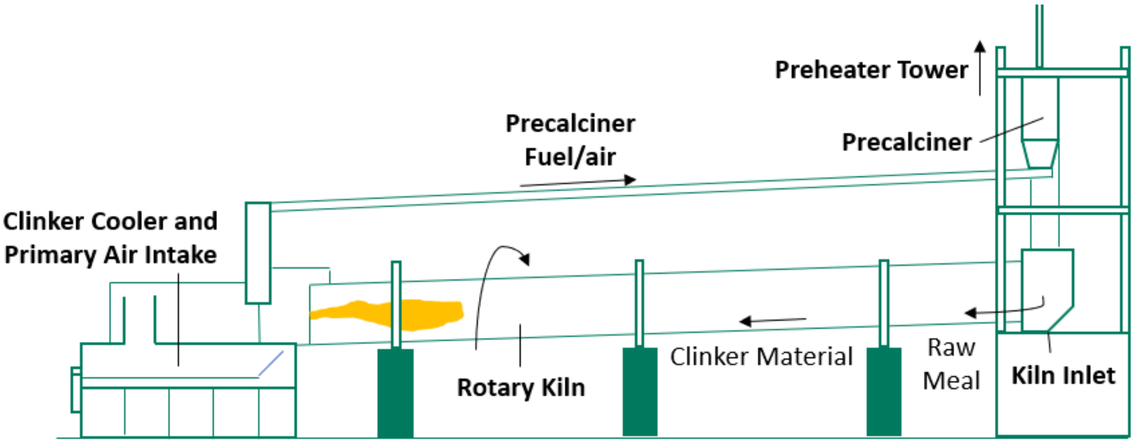


Figure 17: Illustration of a rotary kiln integrated with a precalciner and preheater tower

Rotary Cement Kiln and Precalciner (Pyrosystem)	
Description	The pyrosystem on a cement plant consists of the preheater tower, precalciner unit and the rotary kiln. The precalciner suspends dry meal powder in a turbulent vortex facilitating efficient fuel burning and rapid rates of heat transfer to the powder particles. A rotary kiln is a steel cylindrical drum that slowly rotates at a slight incline, to facilitate the continuous movement of material towards a direct fired burner system. The rotary motion is important to prevent any hotspots and to control the speed of temperature change in the material.
Temperature	A precalciner heats the meal to around 900 °C, mainly by forced convection, at which point the majority of calcination occurs. Temperatures in the kiln go from 1400 °C up to 2000 °C at the flame end to create the intense heat required for clinkerisation.
Production Capacity	The largest cement plant in the UK has a production capacity on the order of 1.4 million tonnes of clinker per year.

Rotary Cement Kiln and Precalciner (Pyrosystem)	
Heat Transfer	Fuel is injected into the precalciner vessel and rapidly mixes with flue gases passing through it. The powdered meal and injected fuel are suspended in the flue gases which create a turbulent mix and flameless conditions. The high surface area and turbulent mixing result in a fast reaction with calcination absorbing the combustion energy instantaneously. A firing pipe passes through the bottom end of the kiln and projects high velocity fuel powder into the kiln. From this, a flame extends into the kiln producing a hot stream of flue gas that directly heats the approaching material. As the material moves down the kiln, closer to the flame, temperatures increase which advances the clinkerisation reaction.
Lifetime	Cement kilns are long lasting and have lifetimes in excess of 25 years.

Electrified alternative – electric arc calcination

The provision of intense heat in a rotary kiln is an essential part of the clinker formation process and multiple initiatives are investigating ways to electrify this process through resistive heating, such as the VTT Technical Research Centre. Another technology under investigation are plasma arcs which can comfortably provide temperatures between 3000–5000 °C. Plasma arc torches operate with a plasma generator. This uses DC electricity to produce an electric arc which raises the temperature of gases passing through the torch and ionises the atoms. Intense heat is radiated from the plasma which can be used for heating industrial processes.

Figure 18: Render of a plasma generator with torch from ScanArc[55]

Plasma torches are commercially available pieces of equipment and are well demonstrated in the metals industry for heating furnaces on the order of 10+ MW. Cementa (Heidelberg Materials) and Vattenfall are developing plasma driven calcination through their CemZero project and have demonstrated clinker production in a small-scale rotary kiln.[56] CemZero project aims to have full scale electrified production of cement by 2030. Elsewhere, the Swedish firm SaltX Technology have succeeded in producing clinker with conventional mineral characteristics[57] using their ‘Electric Arc Calciner’ technology which utilises a plasma torch to produce intense heat to form clinker in a rotary reactor. SaltX plan to open a 2 MW research facility in Q3 2023 and scale to an 8-24 MW plant with by 2025.

Electric Arc Calciner	
Description	An electric arc is used to produce a plasma torch which radiates heat. This can provide sufficient heat to generate the intense temperatures required for calcination and clinker production. One possible configuration of electric arc calciner technology is to integrate the unit between the rotary kiln and preheater tower, substituting a site's precalciner (often the most emissions intensive unit). In this arrangement, the design of the electric arc calciner mimics the design of a traditional precalciner by suspending fine raw meal in a vortex and intensely heating the reactor with a plasma torch. High purity process CO_2 can be separated out from the reactor for storage or utilisation. Plasma arc torches have been investigated for use in the rotary kiln as well and have successfully produced clinker in small scale demonstrations.[56]
Temperature	Plasma torches can operate at 3000-4000 °C to heat the reactor up to sufficient temperatures for calcination and clinker formation.
Production Capacity	Current production capacities are small with 2025 targets of up to 120,000 tonnes of clinker[58] produced annually per reactor. Through increases in reactor size and modularity, larger scales of production are thought to be feasible.
Heat Transfer	The plasma torch produced by an electric arc provides the high intensity heat required for calcination and clinker formation through radiation to the reactor contents. The hot gas exiting the reactor can be utilised in a pre-heating tower to improve energy efficiency in the system.
Lifetime	At this stage of development, the lifetime of reactors utilising plasma torches for calcination and clinker production is relatively unknown. The burner port for plasma torches allows torches to be switched with relative ease for servicing. The reactor vessels are refractory lined and designed to withstand extreme temperatures continuously over the campaign lifetime of the site, as is the case with existing kilns and pre-calciner reactors.

Summary of key engineering data – Electric arc calciner

Data Metrics	Rotary Kiln and Precalciner	Electric arc calciner	Source*
Efficiency	-	~90%	
Capacity	Up to 1,400 kt clinker per year (~250 MW_{th})	120 kt of clinker per year by 2025 (24 MW_{th})	58
Electricity supply requirements	N/A	Three-phase connection, 6-24 kV	
TRL**	9	5 – 6	58
CRI **	6	1 – 2	
Lifetime	30 – 40 years	Not available	
Nominal Capex (incl Installation)	-	£ 4.3 M / MW_{th}	59
Fixed O&M	-	£ 430 k / MW_{th} / yr	59

Data Metrics	Rotary Kiln and Precalciner	Electric arc calciner	Source*
Year of Availability	-	2028 – 2035	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying clinker production

Barriers to deploy electrified clinker production:

- **Significant scale-up will be required in the capacity of the electric arc calciner if it is to meet the production capacities required by large cement sites.** The first planned deployment of the technology in a commercial setting will be the Zero Emissions Quicklime plant with SMA Mineral. This plant could have a production capacity of up to 120 kt of quicklime per year. While this meets the production needs of most dedicated lime production facilities, some large cement sites produce over a million tonnes of lime per year. The reactor size of the electric arc calciner is partially limited by the availability of suitably sized plasma arc torches. A strong demand signal for larger reactor vessels and plasma torches may stimulate research development in this area.
- **Many kilns in the UK will still have significant remaining lifetime and may wish to retrofit an abatement technology rather than completely replace the incumbent equipment**. In these cases, there may be a preference for less disruptive measures such as carbon capture on the full system or fuel switching. The ability of plasma burners to contribute to emissions reduction on existing assets is yet to be determined; however, modelling suggests that plasma torches could be used to provide hot gas for calcination on existing site equipment.[59] Electric arc calciners do not require a complete replacement of the site's major equipment to provide significant decarbonisation – simply by replacing the precalciner and integrating with the existing equipment, a significant portion of combustion related emissions would be eliminated.

Innovation needs for the deployment of electrified clinker production:

- **Innovation should focus on overcoming any technical barriers to meeting the production scale of existing sites.** At the current production capacity, the electric arc calciner doesn't provide a drop-in solution for existing cement sites. Reflecting the commercially sensitive nature of a rapidly developing technology, there is little public information available about the technical barriers to scale-up; however, one of the major determining factors could be limitations on the scale of the plasma arc technology.
- **Some generic considerations that might limit the size of a plasma arc torch are included below:**
    - Plasma arc torches operate at extremely high temperatures and as their size increases, the associated cooling system increases in complexity.
    - In the production of the plasma, a powerful arc is formed between electrodes. As the size and power of the torch increases, the thermal loads on the electrode become more significant exacerbating electrode wear.
    - As the size of the torch increases, maintaining the stability of the plasma becomes more challenging requiring more sophisticated control systems. New design challenges may arise maintaining control of the flow and mixing of gases as the system increases in magnitude.

    - Some plasma torches are designed such that they can be easily removed from a tuyere for maintenance. As torches become larger, the ability to quickly remove and maintain them will decrease.

  These general engineering challenges are not thought to be restrictive on the scale-up of this technology; however, targeted development in material science and control systems will help to overcome them. A strong demand signal for larger plasma arc torch technology will help to justify this research from technical developers.

- **While electric arc calciners have demonstrated full clinker production[60], including sintering, the majority of their demonstrated performance is tailored towards abating the precalciner unit**. By focussing technology development to replace the precalciner, developers have targeted the unit responsible for the majority of a cement site's combustion emissions; however, to achieve full decarbonisation of the pyrosystem's combustion processes, research and development into the technology's capabilities in sintering will need to continue. Achieving the required temperatures of the rotary kiln is not expected to be technically challenging for plasma-arc technology but the system will need to be developed to carefully control the temperature of the meal during sintering as it undergoes phase changes to become clinker. While it is anticipated that electric arc calciners will be able to replace precalciner units and integrate with existing equipment without significant site disruption, the rotary kiln is a major piece of equipment which would require a significant overhaul to replace. To stimulate development of this technology in the application of sintering, a strong demand signal will need to be communicated to technology developers. Since calcination equipment is required for both the cement and lime manufacturing industry, developers currently focus on this application to access a wider market.

Drivers for the deployment of electrified clinker production

- **Removing fossil fuel combustion from the clinker production process means that clinker is not contaminated with combustion products**, improving its quality and strength. Unlike a combustion flame, the plasma jet is unaffected by oxidising conditions within the kiln. In conventional kilns, unmixed fuel and oxidant can lead to tar production and formation of other undesirable compounds.
- **Electrification of heating processes provides an opportunity for dispersed sites without access to H_2 or CO_2 transport infrastructure to remove a portion of their emissions** associated with high temperature heat.
- **Demands on a carbon capture system are greatly reduced for sites that do have access to CO_2 transport and storage infrastructure**, due to lower relative volumes of CO_2 that must be captured and stored with combustion removed. Carbon capture plants favour more concentrated CO_2 streams and the high purity process emissions arising from calcination without contamination from combustion products are much easier to process.
- **The modular nature of electrified reactors can bring operational flexibility and reduce the minimum required investment for a plant to produce cement**. This is particularly suitable for smaller dispersed cement sites.

4.5 Refining

Oil refining is the UK's largest emitting industrial sector, producing a total of 9.9 $MtCO_2e$/year.[8] Activities in the Refining sector are a key contributor to UK industrial output, with 54 million tonnes of crude oil processed per year in the UK and over 8000 staff employed directly.[61,62] There are six major operational refineries in the UK, including: the ExxonMobil refinery at Fawley; the Essar Stanlow manufacturing complex in Cheshire; the Phillips 66 Humber and Prax Lindsey refineries in Humberside; the Valero refinery at Pembroke in Wales; and the PetroIneos Grangemouth refinery in Scotland.[62]

A significant portion of emissions associated with the refining sector arise from its heating processes used to convert crude oil into various intermediate and end-products.

- Roughly 60% of the refining sector's emissions arise from the combustion of hydrocarbons which are comprised of gaseous by-products of refinery processes (internal fuels) and other fossil-fuels (predominantly natural gas).[62]
- The remaining emissions arise from the chemical reactions in the production of hydrogen through steam-methane reformation, regeneration of catalysts and process emissions from other refining processes.
- The main energy vectors for the refining sector are waste refinery fuel gas (47.3%), petroleum coke (24.3%), natural gas (21.3%) and fuel oil (6.7%).[63] The UK refining sector consumes roughly 12 TWh of natural gas and 28 TWh of refinery fuel gas per year.[39]

UK refineries typically produce a product mix that includes, petrol (37%), diesel (25%), kerosene – jet fuel and heating oil (20%), fuel oil (12%), liquid petroleum gas – LPG (3%), and residues such as bitumen.[62] Each refinery in the UK produces a different spread of these products and hence differ slightly in process configuration.

Overview of refining sector processes

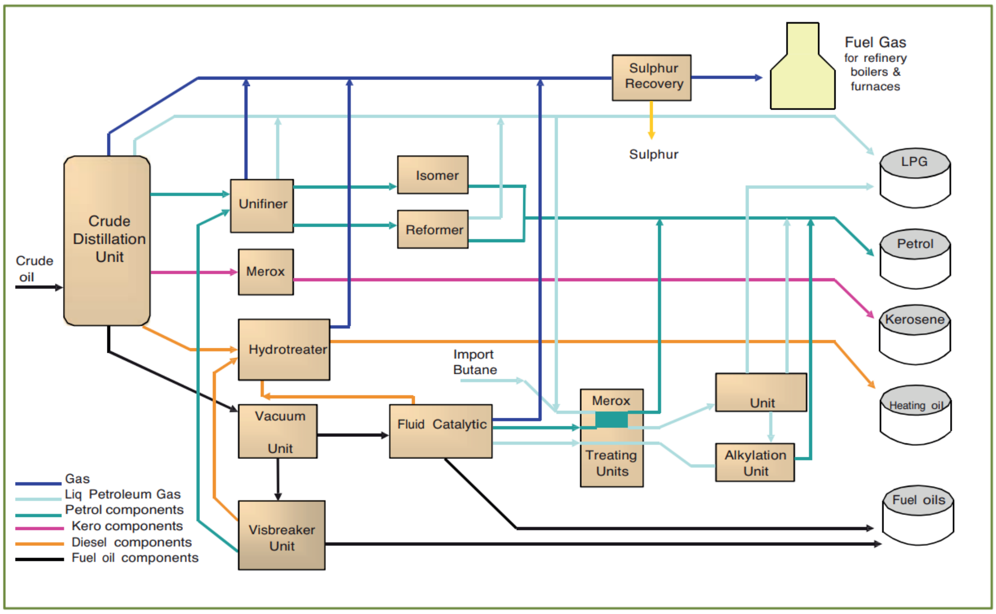


Figure 19: Simplified diagram of typical refinery process units[64], as described below

Figure 19, shows a simplified diagram typical refinery process. The key process units in a refinery process are described below:

- **Atmospheric Distillation Unit (ADU):** In the atmospheric distillation unit (ADU), which is occasionally referred to as the crude distillation unit (CDU), heat is used to vaporise crude oil at 380°C to produce various hydrocarbon fractions.

- **Vacuum Distillation Unit (VDU) and Fluid Catalytic Cracker (FCC):** The heavy residues that settle at the bottom of the ADU (bottoms) are used to produce heavy gas oils and light fuel oil streams at the VDU. The FCC is the main conversion process used to break up these hydrocarbons into lighter products (LPG and petrol components) and a coke-like substance used to turn the heavy components from the VDU to lighter transport fuels.
- **Catalytic Reforming and Hydrotreating:** After having unwanted compounds removed in a unifiner, the petrol components produced in the ADU and VDU pass through either a catalytic reforming unit or hydrocracking units which upgrade the product quality and yield. Hydrogen produced as a byproduct of catalytic reforming is used to reduce the sulphur content of the petrol components in desulphurisation (hydrotreating) units.
- **Steam-Methane Reforming (SMR)**: Some refineries use steam-methane reforming to produce any additional hydrogen they require.
- **Thermal cracking / Visbreaker**: uses high temperatures to reduce the viscosity of some of the heavier fuel residues produced upstream.

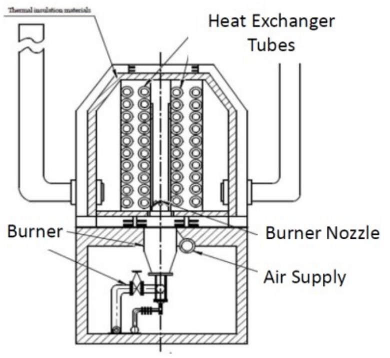
Process emissions from the FCC, catalytic crackers and reformers are responsible for approximately a third of all emissions produced at a refinery. However, these emissions are internally produced from the chemical transformations occurring in these units and hence are not emissions that can be abated with electric heating technologies. The heat required to drive these processes can be abated and is the focus of the electrification solution investigated in the following section.

- The key refinery heating processes that may be applicable to future electrification opportunities are: ADU, VDU, Visbreaking, Hydrocracking, Catalytic Reforming and SMR. These processes cumulatively make up 66% of the combustion related emissions of a refinery with the remainder coming from steam generation (discussed in the previous section)
- The ADU is the most emissions intensive activity of these heating processes, contributing roughly 32% of the total combustion related emissions of a refining process.

The six heating processes listed above all use indirect heating to achieve the required operating temperatures.

Most refinery unit processes require one or more fired heaters and furnaces. In the following section, the operational requirements will be only discussed for the process heater used for the ADU process. This is because, although each of listed process units require a slightly different furnace setup, they all use the same operating principles.

Incumbent heating technology – furnace or fired-process heater

Fired process heater – Atmospheric Distillation Unit		
Description	The primary function of the furnace is to provide enough thermal energy to vaporise crude oil, enabling the separation of different hydrocarbon fractions. The furnace typically uses natural gas and fuel oil in the burner system to produce high temperature flue gases that directly transfer heat energy to crude oil contained in heat exchanger tubes before it enters the flash zone of the atmospheric tower.	 **Figure 20: Illustration of a fired process heater for Atmospheric Distillation Unit[65]**
Temperature	The temperatures reached typically range from 300 – 380°C to heat the crude oil efficiently for distillation.	
Production Capacity	Fawley refinery can process 270,000 bbl_{crude} per day. The theoretical heat required for this ADU is 82 MW_{th}.[66]	
Heat Transfer	Liquid crude oil flows through coiled tubes directly exposed to the flue gases of the combustion radiant box.	
Lifetime	Refinery furnaces last for 20 – 30 years	

Electrified alternative – resistance furnace

The most feasible electric heating technology to abate gas-fired refinery furnaces are indirect resistance furnaces.[67] Direct resistance furnaces for the crude distillation unit are a less likely solution due to the potential material degradation of the heating elements in direct contact with the crude oil at high temperatures. There are several suppliers of high temperature (> 500°C) resistive heating technologies used for the ceramics, automotive and process heating applications. These technologies are in development for industrial applications in the range of 70 MWth such as the system designed by MIDREX and TUTCO SureHeat for hydrogen pre-heating.[68] However, these technologies have not currently been demonstrated for the relevant oil refining applications at the required scale (~100 MW_{th}). Until recently, there has been no industrial demand for large scale electric heating systems, since the high cost of electricity relative to other fuels meant that combustion furnaces were much cheaper to run. This lack of interest meant that there was no incentive for technology developers to pursue such a large electric furnace design. Consequently, there is no standard design of such a furnace and the technology is at a relatively low technical maturity for specific use in oil refineries (TRL 6).[52]

For near-term decarbonisation of the Refining sector, electrification technologies suitable for retrofitting will be advantageous; resistance furnaces could potentially keep most of the features of a conventional furnace, namely the radiant box and the furnace tubes. Radiative heat transfer from heating elements positioned inside the radiant box could be used to heat the furnace heat exchanger tubes. Alternatively, heating elements could be installed directly onto the heat exchanger tubes and heat the crude oil through conduction.

Indirect resistance furnace for ADU	
Description	A potential resistance furnace could either have radiative heating elements lining the furnace walls or use resistance heaters directly attached to the furnace tubes.
Temperature	Resistive heating technology can achieve temperatures up to 3000°C; however, there are no industrial scale deployments of this technology for refinery distillation furnaces.
Production Capacity	There are no industrial demonstrations of resistive heating technology applied at the 100 MW scale in refineries; however, resistive heating has been marketed for other industrial applications at the 10s MW scale.[68]
Heat Transfer	There are resistive heating modules on the market that could be used to line a furnace wall and provide a heating power flux of up to 100 kW/m^2 for furnace temperatures of 700°C.[46] This is within the required operating envelope of conventional gas-fired furnaces.[40]
Lifetime	The lifetime of the resistive heating elements can range from thousands to tens of thousands of hours[69] (up to a few years). However, counterfactual resistance furnaces can have lifetimes well in excess of 20 years.[67] It is likely that the heating elements have a shorter lifetime that other furnace components and thus require a shorter time delay between replacements. The level of disruption this will cause to downstream refinery operations is unknown.

Summary of key engineering data metrics – resistance furnaces

Data Metrics	Gas-fired process heater	Resistance furnace	Source*
Efficiency	75% (LHV) – typical natural gas combustion	>99%	51,67
Capacity	80 – 100 MW_{th} (processing 100,000s bbl_{crude} per day)	Not available for refinery applications	
Electricity supply requirements	N/A	Three-phase connection, 6-24 kV	
TRL**	9	6	52
CRI **	6	1	
Lifetime	20+ years	20 years	51,67
Nominal Capex (incl. Installation)	~ £ 30 k / MW_{th} (excl. installation)	£ 500 k - £4,300 k / MW_{th} (based on a 10 MW_e furnace)	51,70
Fixed O&M	Not available	£ 10 k – £ 100 k/yr (based on a 10 MW_e furnace)	51,67
Year of Availability		2030 – 2035	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying refinery furnaces

Barriers delaying the deployment of high temperature resistance furnaces in refineries:

Existing discussions in the literature on the industrial applicability of resistance furnaces have mostly relied upon desktop analysis, expert consultation, or numerical simulation. An absence of demonstration projects means that the practical challenges of industrial scale implementation have not yet been fully established. Based upon technological differences, challenges to be faced in the development of resistance furnace technology could be expected to include:

- **The current technological concepts for resistance furnaces are at a technological readiness too low for widespread commercial deployment (TRL 6).** While individual heating elements are known to have reliable performance at high temperatures (above 1000°C), further developments are required to establish a sound electric process heater design concept. These developments should aim to answer whether multiple resistive heating elements can be used in a heater design to achieve the thermal heating loads (10s to 100s MW_{th}) required by large furnace applications in refineries, with a suitable longevity.
- The **shorter lifetime of the heating elements relative to the other furnace components may result in disruption to critical refinery operations** (like the ADU) when they need to be replaced. However, planned turnarounds occur roughly every 4 to 6 years on a refinery (for 3 to 5 weeks at a time), therefore this issue can be mitigated by appropriate scheduling to minimise disruptions.[71] The lifetime of heating elements is limited due to their extreme operating temperatures which promotes oxidation, compromising their performance.
- A **significant portion of the fuel used in a refinery onsite is recycled from upstream processes**. Replacing the steam boilers and gas-fired furnaces thus creates a surplus of these waste gases; therefore, when the electrification technologies for refineries are developed to a sufficient level, the solution should be accompanied by an alternative sustainable use for the waste fuel gases. Similarly, hydrogen fuel-switching pathways face a similar barrier regarding the creation of surplus waste gases for which a sustainable use must be found. For these reasons, many have concluded that refineries are more likely to deploy CCS and continue combusting waste fuels.[72]
- The **latest action plans for the decarbonisation of oil refining activities in the UK frequently exclude electrification** from the list of key technology options, focussing more on opportunities for waste-derived or bio-feedstocks, energy efficiency, clustering and carbon capture.[63]
- The **long-term outlook for the production capacity of refineries is likely to be shaped by the end-use market for refinery products**. Decarbonisation solutions targeting the end-use market segment centre around the development of new product and processes that will directly compete with those of the refining sector. As these alternatives develop and penetrate the market, production capacity of refineries may decrease significantly. There is thus a wider question about what decarbonisation pathways (electrification, hydrogen, CCS) can ensure rapid decarbonisation while also being economically compatible with a downscaled refining sector (in terms of minimising stranded assets).
- At the time of writing this report, **there are no demonstrations for indirect electric process heaters for use in a refinery ADU**. However, there are several companies committed to projects focussed on demonstrating high-temperature electric resistive heating, mainly for the electrification of steam cracking. BASF and SABIC have partnered in a 6 MW_e electric steam cracker demonstration project, meant to start-up operations in 2023.[73] Further information regarding this demonstration will be provided in the following section.

Innovation needs for the deployment of high temperature resistance furnaces in refining:

- **The technology to provide indirect resistive heating with the required heat flux exists but has typically been used in smaller scale applications**. To achieve the required heating power on the scale of a refinery furnace, an array of multiple sets of heating elements will be required. The main area for innovation lies in testing and research to determine the optimal set-up of these elements and maximise reliability and performance. The lifetime of electric heating elements is comparatively short relative to the counterfactual combustion system and while refineries have a regular turnaround schedule that can accommodate the replacement of the electric heating system, reliability during operation is paramount. The furnace design needs to ensure that it will continue meeting its heating requirements even if some elements in the array degrade or fail. This will be best achieved by utilising learnings from the largest existing industrial resistive furnaces and developing test equipment to understand how the technology will perform in a refinery specific application.
- **Improving the oxidation and corrosion resistance of electric heating elements will improve the performance and lifetime of the system**. Since the development of industrial resistive furnaces in the early 20th century, an active area of research has sought to improve the resistance of heating elements against oxidation and corrosive attack. This mode of failure is particularly prevalent at high temperatures and is highly detrimental to the system's heating performance so any further material innovations in element design will be beneficial to the performance of resistive furnace and promote their application.

Drivers for the deployment of high temperature resistance furnaces in refining:

- A **decrease in the formation of contaminants within the fuel system** can be achieved by electrifying the heating process. Combustion systems can result in the deposition of coke and other contaminants on the interior surface of the fuel pipes due to the presence of hot spots. Coking can lead to system failures and downtime which is highly costly to a refinery.
- **Increased temperature control** can be achieved with electrified systems which can respond rapidly to system changes to vary their heat output. The ability to quickly respond to system changes and maintain stability is highly valued in refinery processes, bringing improvements in productivity and safety.
- Electrified heaters can **eliminate combustion emissions from a furnace process completely**. This can lower a refinery's dependence on other abatement options such as carbon capture and low carbon fuels, both of which bring their own application challenges in the context of a refinery's process flow.

4.6 Glass

The glass manufacturing industry in the UK is a significant sector, producing 3.5 million tonnes of molten glass each year and providing direct employment for around 6,000 people.[74] The UK industry comprises 10 distinct manufacturers, which together operate 17 facilities; large portion of which are based around Leeds, Sheffield and Liverpool.

The industry is highly energy intensive, with an annual natural gas consumption of around 6 TWh and an electricity demand of around 1 TWh.[74] As a result, the glass manufacturing sector is one of the UK's largest industrial emitters, producing a total of 1.3 $MtCO_2$/year. These emissions stem from various processes such as combustion, material degradation and on-site electricity generation. Many end-customers are increasingly pressing the glass manufacturing industry to reduce the embodied emissions of their glass products.

Broadly speaking, the industry can be divided into three subsectors: container glass, flat glass and glass fibre. Further speciality products are also produced at small scale. Of the three main subsectors, the most significant for UK production are container glass and flat glass:

- **Container glass** products consist of bottles and jars, mainly produced for the food and drink industry. This form of product represents roughly 65%[75] of glass manufactured in the UK.
- **Flat glass** is mainly produced in optically clear sheets used for windows in the automobile and construction industries. This represents around 30%[75] of the UK's glass production.

Overview of glass manufacturing processes

To understand electrification opportunities, it is important to clarify the overall production process. While specific site operations vary depending on product requirements, there are multiple common steps in the production process which are outlined below:

Figure 21: Schematic of common production steps in glass manufacturing, as described below

An explanation of each step is as follows:

- **Batch Preparation**; glass production begins with input of the dry raw materials (mainly silica sand with some sodium carbonate and limestone), which are crushed to a fine grain and mixed in specific proportions to ensure optimal conditions for melting and fining. For products with specific physical properties or colours, additives can be included to the mix. Recycled glass is referred to as cullet and may be internal (returns from the factory line) or external (collecting from recycling centres). Colour separation and contaminant removal are important processes to ensure that external cullet does not adversely affect the batch. The processes at the batch plant are typically completely electrified and may contribute ~4% of the plant's total energy usage.
- **Melting and Fining**; the batch material is fed into one end of a furnace where it is heated at temperatures of up to 1,700 °C causing it to melt into a bath of molten glass. The role of the melting furnace is to provide the glass forming units with a homogenous-melt, free of bubbles, crystalline defects or impurities. For this to occur, the material needs sufficient residence time to circulate within the melt-bath of the furnace, allowing complete dissolution of sand grains. 'Fining' pertains to the diffusion and dissolution of gas from the melt into bubbles which can rise and escape. Before leaving the furnace, the glass melt is drawn by gross glass flow to the forehearth where controlled cooling brings the temperature down, ensuring thermal homogeneity. This ensures a consistently uniform viscosity in the melt before the forming

process. Note that in the case of flat glass, the glass-melt requires a particularly high residence time to ensure complete fining and homogenisation. While melting and fining occur in the same zone of the furnace for container glass production, the fining process occurs in a distinctly separate portion of the furnace for flat glass production.

- **Forming (Container Glass);** to produce container glass, molten glass is directed through multiple feeder channels from the furnace to forming machines. These machines comprise iron moulds into which compressed air is injected, causing the molten glass to take the shape of the desired hollow container.
- **Forming (Flat Glass);** to make flat glass, glass-melt flows down a canal from the forehearth over a refractory spout onto a float-bath. In the float-bath, the glass is suspended on an immiscible layer of molten tin producing flat sheets with a high-grade surface finish. Following this 'float glass process', glass exits the float bath in the form of a semi-solid ribbon.
- **Post-Forming and Finishing;** these steps typically involve an annealing process followed by a mix of possible coating, tempering, laminating and polishing procedures. During the forming process, temperature changes induce stresses within the glass which can be relieved by annealing. The annealing process involves preheating to relax the stresses within the glass, followed by controlled cooling in a lehr to avoid inducing any significant temperature gradients across the material.

It is important to note that ~85% of the UK glass sector's energy consumption is for direct heat production,[75] with the **Melting and Fining** stage being the most energy-intensive. The stage alone accounts for about 80% of the plant's direct emissions, and thus represents a significant opportunity for decarbonisation in the glass sector.

Incumbent heating technology – gas-fired glass melting furnaces

In the **Melting and Fining** step, gas-fired melting furnaces are used, with different types employed depending on the use case. It is useful to first clarify what factors can vary between different furnaces. Gas-fired furnaces are distinguished by three main factors: burner position, burner type and mode of heat recovery.

- **Burner position:** For the burner position, there are two main variations. In the cross-fired approach burner ports are positioned in staggered fashion along each length of the furnace, with flames extending across the width of the tank. Alternatively, end port-fired furnaces (U-flame) position their burner nozzles at the back wall side and flames extend the length of the furnace. At the front wall, the combustion flow direction turns, forming a U-shape with the flame.
- **Burner type:** Furnaces can also differ in the 'burner type' – essentially the oxygen source for gas combustion. Air-fuel furnaces draw air in directly for combustion, whereas oxy-fuel furnaces utilise pure oxygen which results in reduced flue gas volumes.
- **Heat recovery:** Gas-fired melting furnaces employ different strategies to reduce the amount of heat wasted in the exhaust flue gas; there are two main designs for heat-recovery: regenerative and recuperative furnaces. Regenerative furnaces utilise regenerator chambers which are filled with stacks of refractory brickwork. Hot flue gases pass through the chamber and heats the bricks, storing thermal energy. When combustion air is drawn over the hot bricks it is heated prior to combustion. A recuperative furnace operates with a large heat exchanger to transfer heat from the hot flue exhaust to the incoming combustion air. Although these measures increase the complexity of the furnace and restrict access to the furnace structure, without them, the efficiency of gas-fired furnaces would be particularly low.

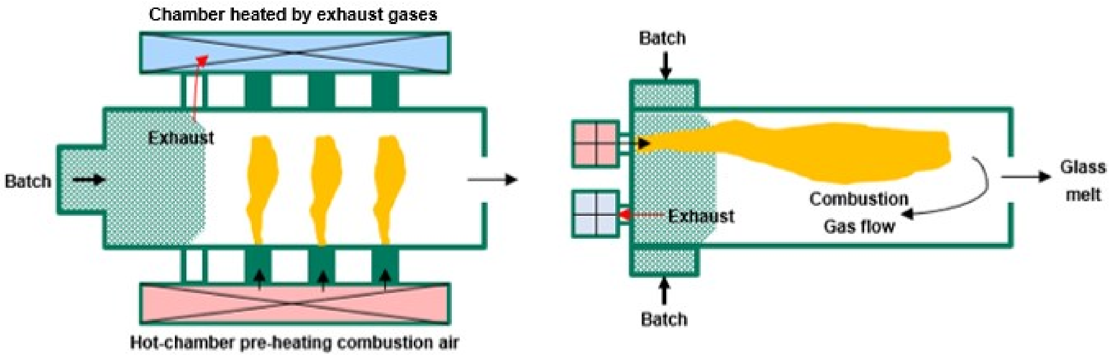


Figure 22: Top view of cross-fired (Left) and end port-fired (Right) furnaces with regenerator chambers. Batch materials are charged from the left-hand side of the image while glass melt is drawn from the furnace on the right.

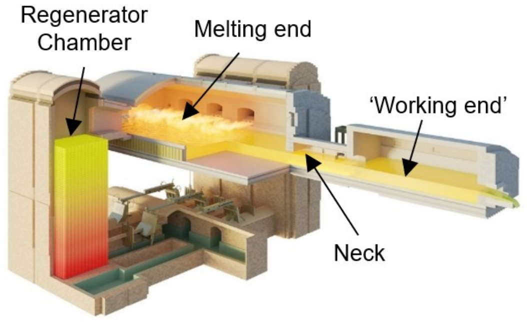
Flat glass is typically produced in regenerative cross-fired furnaces with an open connection to the refining section, known as the 'working end'. Glass leaves the furnace at a spout at which point it enters a float-bath for forming. The furnaces often have a large tank footprint with melting areas in the order of 300-400 m^2. **Container glass may be produced in a range of furnaces**; however, unlike a flat glass furnace, the container furnace contains a throat that provides a degree of physical separation between the melting end and working end. Furthermore, feeder channels provide temperature control for the glass melt as it is transported to forming moulds.

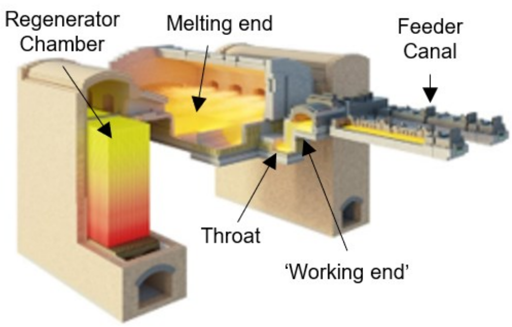
In the melting end of a gas-fired glass furnace, temperatures can be as high as 1,700 °C. Such temperatures are crucial for effective batch material melting, dissolution of all sand grains, and removal of gas bubbles in the melt to ensure high quality glass is formed. Temperatures are reduced before glass leaves the furnace to bring the melt to the appropriate temperature for forming.

In terms of capacity, flat glass furnace production capacities are typically larger – in the range of 600-800 Tonnes Per Day (TPD). These high capacities are enabled by the large furnace dimensions, which also help to minimise heat loss. Higher quality glass requires a longer residence time in the furnace and consequently the specific melting capacity of a flat glass furnace is lower than that of a container glass furnace (4 $t/(m^2 \cdot d)$ and 2 $t/(m^2 \cdot d)$ respectively[76]). **Container glass furnaces are typically smaller than flat glass furnaces** and produce 200-400 TPD, but there are exceptions. For example, the largest container glass furnace in the world is 900 TPD, operated by Encirc in Cheshire. Container glass can afford a lower residence time in the furnace as the quality requirements are typically less stringent.

For both glass types, the heat transfer method is radiant heat transfer from the flames to the glass melt beneath. The upper part of the furnace superstructure (the crown) is heated by the flames and also radiates heat back down onto the melt. Efficient heating of the melt is particularly important for optical quality in flat glass production and furnace design features are exploited to navigate the glass flow through the hottest point of the furnace.

Conventional flat glass melting furnaces last for up to 20 years before a partial rebuild is required due to degradation of the refractory lining.[75] Following two ~20 year campaigns, a full furnace rebuild is needed. Production is continuous and once the furnace reaches temperature for the first time, this temperature must be sustained for its lifetime. If temperatures are allowed to drop and the glass solidifies, the furnace will be critically damaged. Container glass melting furnaces typically have a slightly smaller lifetime of up to 15 years. As with flat glass furnaces, production is continuous, and the furnace temperature must be sustained continuously throughout the lifetime.

Gas-fired Flat Glass Melting Furnaces		
Description	Flat glass is typically produced in regenerative cross-fired furnaces with an open connection to the refining section, known as the ‘working end’. Glass leaves the furnace at a spout at which point it enters a float-bath for forming.	 **Figure 23: Illustration of a regenerative cross-fired flat glass furnace[77]**
Temperature	Up to 1700 °C required at the melting end	
Production Capacity	Typically, in the range of 600-800 TPD.	
Heat Transfer	Radiant heat transfer from the flames heats the glass melt beneath it.	
Lifetime	Up to 20 years	

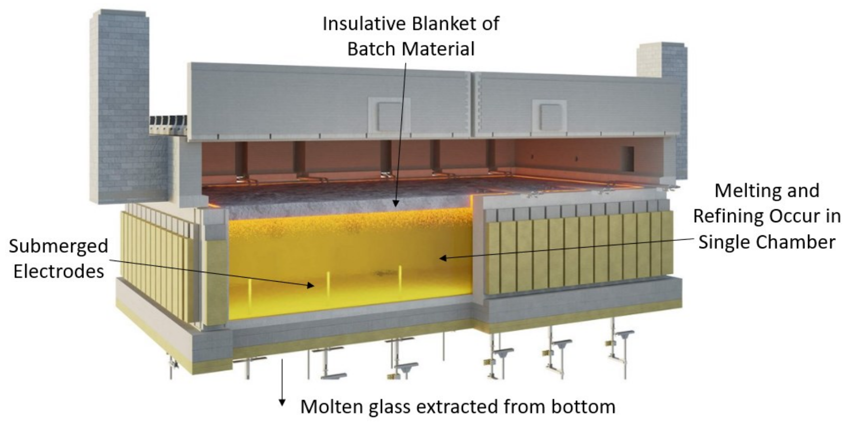
Gas-fired Container Glass Melting Furnace		
Description	Container glass may be produced in a range of furnaces; however, unlike a flat glass furnace, the container furnace contains a throat that provides a degree of physical separation between the melting end and working end. Feeder channels provide temperature control for the glass melt as it is transported to forming moulds.	 **Figure 24: Illustration of a regenerative cross-fired container glass furnace[77]**
Temperature	Up to 1700 °C required at the melting end	
Production Capacity	Typically, smaller than flat glass furnaces and produce 200-400 TPD	
Heat Transfer	Radiant heat transfer from the flames heats the glass melt beneath it.	
Lifetime	Up to 15 years	

Electrified alternative – electric glass melting furnaces

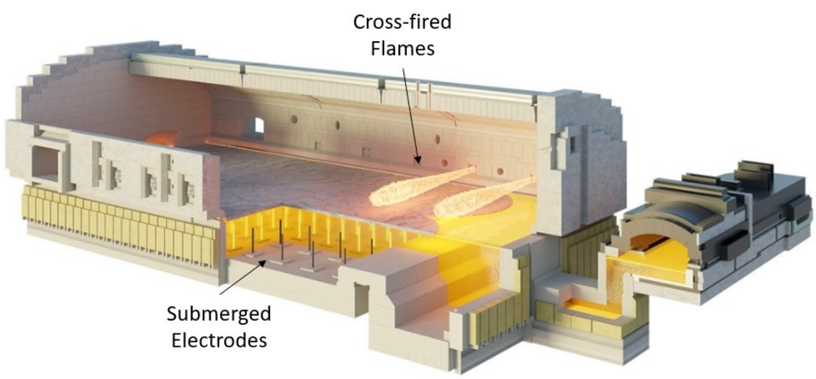
An electrified alternative to gas-fired melting furnaces are Cold-Top Vertical Melting furnaces (CTVMs). These furnaces are a well-demonstrated technology at commercial scale and historically have been used to produce premium container glass and speciality glasses. The melting process is 'vertical', meaning that a uniform blanket of batch materials is maintained at the top of the furnace. This material is melted and refined as it travels down the height of the furnace before exiting as molten, homogenised glass at the bottom via throats and channels connecting to forming machines.

Heat transfer in CTVM furnaces is very different to gas-fired furnaces. In CTVMs, submerged electrodes (usually positioned vertically) conduct a current to the melt, directly heating it. Glass-melt near to the electrodes decreases in density as it is heated causing it to rise and form convection currents within the tank. Heating is controlled simply by the electrode power (kW) which is reflective of the resistive power dissipated by the surrounding melt. The batch material provides a thermally insulative blanket over the top of the melt which prevents heat losses to the superstructure. Notably, this method of **heat transfer is much more efficient than** the counterfactual **radiant transfer**, where heat is lost to the furnace structure and flue gases.

CTVMs are typically used to make container glass as well as speciality glasses. The glass produced from all-electric furnaces is noted to be of higher quality than what can be achieved in conventional gas-fired furnaces. The insulating batch blanket in the CTVM means that any volatile gases are cooled and condense as they pass through the batch, returning to the melt.

Cold Top Vertical Melting Furnaces (CTVMs)	
Description	The melting process is 'vertical', meaning that a uniform blanket of batch materials is maintained at the top of the furnace. This material is melted and refined as it travels down the height of the furnace before exiting as molten, homogenised glass at the bottom via throats and channels connecting to forming machines.
	 **Figure 25: Illustration of a Cold Top Vertical Melting Furnace[77]**
Production Capacity	CTVMs for container glass production currently have capacities of up to 300 TPD.
Heat Transfer	Electrodes (typically positioned vertically) pass a current through the glass-melt around them, dissipating heat from the electric resistance of the melt.
Lifetime	CTVMs have lifetimes in the order of 7-8 years.

The vertical melting/refining structure of CTVMs is unsuitable for producing flat glass which requires horizontally orientated processes to facilitate the carefully controlled melting and refining that this product requires. Another furnace alternative is to combine gas-fired and electrified elements to create a 'hybrid' furnace which capitalises on the strengths of both approaches. Raw batch materials are fed from one end of the furnace into the melting tank and do not conduct electricity meaning that a flame is required to provide a degree of preliminary heating before the batch has formed part of the melt. Once molten, submerged electrodes supplement the heat transfer from the flames and keep the melt hot through a process called 'boosting'. The manner in which the electrodes heat the melt is the same as with a CTVM furnace - passing a current through the molten glass to generate heating within the melt directly. Electric boosting has conventionally contributed up to 50% of the share in thermal power; however, modern designs can have electric shares above 80%.

Hybrid Glass Melting Furnace	
Description	Hybrid furnaces combine gas-fired heating with electric power supplied by electrodes submerged in the melt. Unlike CTVM furnaces, the production process is 'horizontal' maintaining high furnace residence time and facilitating integration with conventional float baths.
	 **Figure 26: Hybrid Glass Melting Furnace with cross fired burners and submerged electrodes[77]**
Production Capacity	Hybrid furnaces can achieve roughly the same capacities as conventional gas-fired flat gas furnaces, with some hybrid furnaces expected to achieve 1000 TPD +.
Heat Transfer	Radiant heat from flames and direct heating from submerged electrodes.
Lifetime	For hybrid furnaces with high levels of electric boosting (>70%), campaign lifetimes will be comparable to an all-electric furnace (7-8 years).

Summary of key engineering data metrics – Cold Top Vertical Melting Furnace

Data Metrics	Gas-fired flat glass melting furnace	Cold Top Vertical Melting Furnace	Source*
Efficiency	20-48%	75 – 85 %	76
Capacity	600-800 TPD (~33 MW_{th})	300 TPD (~14 MW_{th})	77
Electricity supply requirements	N/A	Three-phase connection, 6-24 kV	

Data Metrics	Gas-fired flat glass melting furnace	Cold Top Vertical Melting Furnace	Source*
TRL**	9	9	78
CRI **	6	6	
Lifetime	20 years	7 – 8 years	78
Nominal Capex (incl Installation)	-	1.04 £M/MW_{th}	79
Fixed O&M	-	0.42 £M/MW_{th}	79
Year of Availability		2024 – 2028	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying glass melting

Barriers for electric glass-melting furnaces:

- **CTVM furnaces have not been demonstrated commercially with production capacities greater than 300 TPD.** This is partially due to a lack of demand for large furnaces; however, some technical limitations remain for increasing capacity. The vertical melting process necessitates a deep melt tank and as the furnace capacity increases, so too will the tank's height. As the furnace increases in height it will become more structurally complex to handle the increased hydrostatic pressure of the glass melt contained within. Access to the furnace for maintenance and rebuilding of the refractory lining also become more challenging as the height of the furnace increases. For furnaces with a larger footprint, it is also more difficult to evenly distribute batch material. It is thought that as furnaces get larger and electrodes become further separated, it will become more challenging to control the thermal flows within the glass-melt. While these issues restrict the maximum capacity of CTVMs, the merits of increasing CTVM furnace capacities much beyond the current limit of 300 TPD are diminished. Unlike gas-fired furnaces, all-electric furnaces achieve little efficiency gains with increases in furnace capacity as little energy is lost to the superstructure. Production with multiple smaller parallel units has many performance advantages and improves plant reliability. The ability to have modularity means that there are no particular barriers to CTVMs meeting any required scale of production.
- **CTVM furnaces struggle to operate at high cullet levels** and perform best when the proportion of recycled glass (cullet) is kept to a maximum of around 80% of the batch, preventing these furnaces from completely operating on recycled glass. The batch material forms a layer completely covering the glass surface in the upper part of the furnace; this insulates the melt. However, high proportions of cullet make the batch layer overly transparent allowing heat to be transferred from the melt to the superstructure by radiation. The UK exports a lot of its clear glass and green glass (from wine bottles) has the largest market share in terms of domestic consumption. This means that available cullet is typically more likely to be green and furnaces operating with high cullet levels tend to be for the production of green glass (~18% share of domestic production). A portion of these furnaces will operate at cullet levels >80% which will be restrictive to CTVM furnaces.
- **Reduced (amber) glass production can be challenging in CTVMs**; a gas release occurs during melting reactions in the batch layer that results in foaming. This can destabilise the batch blanket making it difficult to maintain an effective batch covering. Amber glass has a market share

of ~17% in the UK.[75] Despite the challenges that amber glass can present, large electric furnaces have been shown to overcome these issues with adaptions to batch compositions and furnace design enabling the stable production of amber glass over multiple years.[80]

- **Electric furnaces have shorter lifetimes than their gas-fired equivalents due to increased refractory wear from corrosion;** higher flow velocities and operating temperatures in electric furnaces mean that the furnace wall requires rebuilding after a shorter duration. Despite the shorter lifetime, the cost of all-electric furnaces and their repairs is much cheaper than gas-fired furnaces and rebuild times typically last less than a month.
- **For horizontal furnaces, submerged electrodes will struggle to supply 100% of the furnace's thermal input, requiring a secondary heat source.** Electrodes generate heat in the melt tank by conducting a current through the molten glass, generating heat within the glass itself by ohmic heating. If the glass is not in a molten state, it will not conduct electricity effectively and while heat from the melt can partially heat solid batch material through conduction; however, another form of heating is required to efficiently melt the batch. For this reason, hybrid-furnaces with high levels of electric boosting (up to 80% of the furnace's thermal energy from electrodes) currently require some gas-firing. With current designs, some alternative heat source will be required to provide the intense heat needed to initially melt the batch material while it is in a solid, non-electrically conductive state.

Innovation needs for the deployment of electric glass-melting furnaces:

- **The production capacity of CTVM furnaces is limited to ~300 TPD by multiple technical factors. While there are many advantages of operating with smaller furnaces, for an individual CTVM furnace to reach higher capacities the following technical developments would be required:**
  - Technological developments will be required to design a system that can evenly distribute batch material across the melt surface for any CTVM furnaces that require a particularly large footprint. This is thought to be an innovation that should be easily achieved. This innovation is only required for particularly large CTVM furnace designs while furnaces at the current capacities (<300 TPD) are capable of distributing batch material without any further innovations required.
  - Computational Fluid Dynamics software will help furnace designers to better understand the impacts that increasing electrode spacing has on thermal flows within the glass-melt. This can help to guide the design of furnaces as their capacity increases as well as determining the optimal positioning of electrodes to reduce refractory wear induced by high glass flows.
- **Innovations reducing refractory wear will help to increase the lifetime of CTVM and hybrid furnaces**. Wear at the furnace walls can be partially reduced through optimised electrode positioning. An area of active development, optimal positioning can be determined through computational modelling. Computational modelling can also aid in modelling the likely location of corrosive attack in the tank and facilitate an appropriate mitigation strategy including more targeted placement of patching tiles in maintenance. Continued research in material science could improve the lifetime of refractory materials by improving their corrosion resistance. Ensuring that high grade, void free refractory materials are used will reduce the susceptibility of the material to corrosive attack.
- **Developments in the performance and understanding of electric boosting should be pursued to maximise its decarbonisation potential in the flat glass sector**. Electrode heating in horizontal furnaces is the most efficient way of heating the glass melt; however, other modes of heating will be required for the initial melting of raw materials. Research and pilot projects will be required to establish the optimal way of achieving this, whether this is

through another form of electric heating or fuel switching gas to an a low-carbon fuel alternative such as hydrogen.

Drivers for the deployment of electric glass-melting furnaces

- **Electric glass melting is significantly more energy efficient,** by utilising heat from electrical resistance within the glass melt itself, inefficiencies such as heat losses in flue gases and to the furnace structure are minimised.
- **Electric furnaces maintain high energy efficiency even at smaller production scales enabling sites to operate multiple smaller furnaces in parallel for increased site flexibility.** Counterfactual gas-fired furnaces have a significant drop off in efficiency as their production scale is reduced (17% efficiency for a 10 TPD furnace) meaning that very large furnaces are necessary to achieve reasonable levels of fuel consumption. For a site operating a single large furnace, production ceases completely when the furnace requires relining and it much more difficult to produce multiple glass types on the same site. Electric furnaces are highly energy efficient even down to very small scales of production (~ 75% efficient for a 10 TPD furnace) meaning that it is economically feasible to run multiple smaller furnaces in parallel rather than one large electric furnace. This provides increased flexibility in the product range a single site can produce and allows staggering in the maintenance schedules on the furnaces, minimising down time.
- **Electric glass furnaces produce a higher quality of glass than conventional furnaces;** the manner of heat transfer in electric furnaces enables more effective heat transfer and brings an improvement in homogenisation and particle dissolution leading to a higher quality of glass product.
- **Electric furnaces have no requirement for large heat recovery equipment** such as regenerator chambers and recuperators; this reduces capital expenditure, simplifies the plant footprint and makes the furnace structure more accessible.
- **Electric furnaces have improved control over volatile compound release due to the insulative effect of their batch layer;** the batch layer prevents the top of the furnace from getting hot meaning that volatile compounds rising through the upper layers of the batch material condense before they can escape. This provides capital and operational cost savings on equipment such as acid scrubbers used for treating exhaust gases.
- **Electric heating has some inherent advantages over alternative abatement measures.** Hydrogen flames provide significantly less radiative heat transfer than a hydrocarbon flame and is a much less efficient method of getting heat into the melt than with submerged electrodes. Carbon capture systems are expensive and increase the system complexity even further.

4.7 Food and Drink

The food and drink industry is one of the largest manufacturing sectors in the UK, accounting for over 18% of the annual turnover of the total manufacturing sector. The industry employs close to 400,000 people and has a gross value added (GVA) of roughly £ 28 billion.[81] The sector currently counts over 7,800 companies and has at least 160 sites operating in the UK (these are just the sites reporting on the NAEI database).

Roughly 70% of the total sector energy use is from fossil fuels, with electricity accounting from the remaining energy use.[82] The fossil fuel use in this sector is mainly directly towards heat production and natural gas is the dominant fuel source, contributing roughly 83% of the fuel demand.[39] For sites with limited access to the gas network, the fuels used tend to be LPG and gas or fuel oils. This fossil fuel use makes it one of the largest emitting sectors with around 3 $MtCO_2$/year for all food, beverage and tobacco activities.[8]

Overview of food and drink processes

The food and drink activities are characterised by having a large variety of subsectors using numerous different processes. This is true even between sites producing similar products. The main unit operations applied throughout this sector include, but are not limited to, the following processing steps:[82]

- Material handling and preparation
- Size and form management
- Separation techniques
- Product processing
- Heat processing
- Concentration by heat
- Chilling and freezing
- Post-processing
- Utility processes

Within each of the listed processing steps there is a significant number of unit operations and processing techniques used that are very specific to certain subsectors. Given this diversity between subsectors and processes, it is appropriate to narrow the focus of analysis on the most relevant processes for electrification opportunities. This includes processes that generate CO_2 emissions onsite, such as gas-fired combustion to generate heat, but excludes processes like fermentation which are intrinsic to the production of the final product. **Approximately 46% of the useful energy demand in this sector is used for steam generation as well as direct-fired drying and ovens.**[9] These processes take a slightly different form depending on the given subsector. Steam generation is a trans-sectoral heating process and has already been discussed in much detail earlier in the report (see section 4.1). The incumbent heat technology discussed in this section will discuss direct-fired dryers and ovens. Large scale gas-fired dyers and ovens are heating chambers designed to remove moisture from food products and facilitate cooking or baking processes.

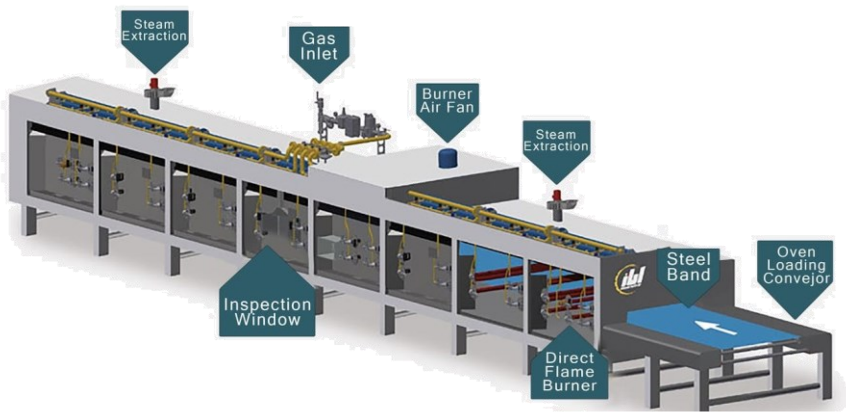
Incumbent heating technology – Baking Oven

As mentioned, there is a large diversity of heating technologies for food and drink production processes. As such, in this report, a conventional baking oven/dryer was chosen as the incumbent technology for which to investigate electrification opportunities.

Conventional baking ovens transfer the heat from a combustion process to the target material through a mixture of convective, radiative, and conductive heat flux. In direct gas-fired ovens, the ratio between these different fluxes is controlled by the flowrate of the incoming gas and the recirculation and extraction rate of the air in the heating chamber. An additional requirement is also the length of time being exposed to the oven's heating conditions.

<table>
<tr><th colspan="2">Baking oven</th></tr>
<tr><td rowspan="2">Description</td><td>Ovens and dryers work on the principle of convection heating where hot air is circulated within the oven chamber to transfer heat to the food items.

Some ovens may be open with the combustion products coming into direct contact with the products while others may be closed – the combustion indirectly heats air which is forcefully convected.

Impingement is where hot air is blasted onto the food through a nozzle resulting in much faster baking/drying times.</td></tr>
<tr><td>
Figure 27: Schematic of a direct-fired industrial gas oven[83]</td></tr>
<tr><td>Temperature</td><td>Typically, ovens may operate in the temperature range of 100 – 300 °C. Some specialised industrial ovens can achieve higher temperatures depending on process requirements (up to 1000°C is used in sugar beet pulp drying – not baking).[84]</td></tr>
<tr><td>Production Capacity</td><td>Processing capacities can range from a few hundred kilograms to several tons of food product per hour. Larger scale units are likely to be continuous while smaller sites may operate batch ovens.</td></tr>
<tr><td>Heat Transfer</td><td>For the bulk cooking time, for an example of Burton's Foods baking ovens, the heat flux roughly fluctuates between 2.5 - 6 kW/m^2 and 4 – 8 kW/m^2 for radiative and convective heat transfer respectively. The overall heating efficiency of these ovens was found to be roughly 40%.[85]</td></tr>
<tr><td>Lifetime</td><td>Ovens can last for 20+ years.</td></tr>
</table>

Electrified alternative – Microwave Dryer

Microwaves represent the subset of electromagnetic radiation with frequencies between 300 MHz and 30 GHz. In practice however, only a discrete set of frequencies are reserved for use in scientific, medical and industrial microwave applications.[86] Domestic microwave systems operate at 2.45 GHz whereas UK industrial systems use the 896 MHz frequency (915 MHz is commonly used in North and South America).

Microwave systems work by creating heat from within the target material, described in more detail in section 2. These systems have seen successful widespread deployment for industrial processing in the food sector since the 1970s. There are several companies (Ferrite, Dantech and MAX industrial microwave) designing these systems for numerous industrial food processing applications such as:

- Pasteurising ready-made meals
- Drying snack and vegetables
- Baking and proofing dough
- Meat and poultry cooking
- Tempering meat, poultry, fish, fruit
- Bacon precooking

Drying is the process by which liquid in a material is evaporated. Microwaves systems are very well suited to significantly decrease the drying time for various food products compared to conventional drying techniques. In conventional drying methods, the drying speed is limited by the rate at which the liquid inside the material diffuses outwards to the surface where it is evaporated. The ambient temperature of the drying environment affects the rate of evaporation and hence also impacts the drying speed. In microwave drying, the target material is exposed to an oscillating microwave field that generates internal heat in the material. This creates an internal pressure gradient within the material that pumps the liquid out towards its surface. In conventional drying, hot air is used to evaporate the surface liquid whereas in microwave heating hot air is used to transport liquid out of the dryer. This allows the required drying temperature to be 50 - 80°C lower than conventional drying.[86]

In microwave drying, the magnitude and uniformity of the power absorbed by the food products is affected by several food specific factors. Amongst these are the material's volume, surface area, aspect ratio (surface area/volume) and dielectric properties (polarity of the constituent molecules of the material).

Microwave Dryers	
Description	A microwave dryer is comprised of three parts, namely, the generator, the waveguide, and the applicator. The generator converts electricity to electromagnetic microwave radiation. The waveguide is the mechanism that transfers the power from the generator to the heating chamber or applicator. The applicator is a controlled environment in which the microwaves bounce around, thereby drying the target material.
Temperature	In the microwave applications listed above, the drying temperatures can be up to 200°C, depending on the product requirements. However, microwave systems can achieve temperatures up to 2000°C.
Production Capacity	Capable of processing 100s – 1000s kg food per hour. The largest microwave generators can deliver up to 100 kW per unit. These heating systems are typically modular in that multiple generator units can be used for a given production line. The upper limit of heating capacity of a microwave system is set by economic, rather than technical factors. Ferrite's MIP11 system can generally process up to 820 kg of product per hour and markets microwave system design options with a power of 600 kW and above (on request).[87]
Heat Transfer	The movement of the microwaves within the environment of the applicator, rapidly oscillates molecules within the food product (primarily water) thereby creating heat within the material itself.
Lifetime	Industrial magnetrons, a critical component of microwave generators, typically experience lifetimes of around 5000 to 6000 hrs (roughly 9 months of 24/7 use).[86] The wider, non-microwave generating, system components (insulated cavity, conveyor system, air dryer system etc) typically have longer lifetimes of 10 – 20 years.

Summary of key engineering data metrics – Microwave dryer

Data Metrics	Gas-fired baking oven	Microwave dryer / oven	Source*
Efficiency	~40 %	~70%	85,87
Capacity	100s – 1000s kg food per hour (up to 4 MW_{th})	Several 100 kW_{th} transmitters (100s – 1000s kg food per hour)	87
Electricity supply requirements	N/A	Singe / Three-phase connection, low voltage	87
TRL**	9	8 - 9	
CRI **	6	1 – 2	
Lifetime	+ 20 years	10 – 20 years for the system; however, magnetrons require ~annual replacement.	86
Nominal Capex (incl Installation)	Not available	Not available	
Fixed O&M	Not available	Not available	
Year of Availability		2023 – 2030 (depending on product)	

**Where manufacture or literature sources have not been identified, the relevant data metric has been estimated based on ERMs cumulative evaluation of the literature.*

***TRL/CRI – technical readiness level / commercial readiness indicator, based on grading used by Figure 29*

Specific barriers, innovation needs and drivers for electrifying food drying

Barriers delaying the deployment of microwave oven technologies in the food and drink sector:

As mentioned earlier, the food and drink sectors are characterised by significant product diversity and processing units. Since microwave technologies have seen vast deployments in industrial applications, the barriers facing the technology have less to do with its technical capabilities and more to do with its product suitability and economic case. There are three main barriers limiting microwave deployment in food processing applications:

- **Replicating the product quality**: The food and drink sector is heavily reliant on its ability to manufacture products of consistent and high quality. Hence, manufacturers that are considering decarbonising their unit operations are evaluating whether the alternative technology can match the incumbent in terms of product quality. The type of heating mechanism from microwave systems tends to leave the surface temperature of the material relatively cool, compared to the internal temperature, which limits its application for products requiring some surface heating (i.e., products requiring a characteristic fried or charred look). However, this ability also makes microwaves better suited for some other food products where it is beneficial to avoid overheating the surface (i.e., precooking meats / poultry, tempering meat, baking).

Burtons Food Limited Case Study	
A detailed industrial fuel switching study was conducted by 42T and Burton's Foods Limited (UK biscuit baker)[85], giving a detailed characterisation of the operating requirements of their current industrial baking line. The study concluded that any electrified baking alternative needs to match the incumbent technology in the following key parameters to meet the stringent product quality requirements:	
• Heat flux	• Air speed
• Temperature	• Humidity

- **Site specific economic reasons:** While microwave systems have been tested and deployed across multiple product types, they have fallen out of use in several subsectors despite achieving the required product quality. The reasons are often very niche and process specific, but they generally relate to certain process parameters that ultimately increase the overall cost of production despite the specific benefits of microwave heating. One such example is from a United States case study of deploying microwave technology in bread baking process. It was shown that implementing microwave baking would result in a significant gain in energy savings as well as increased food throughput. However, the resulting increase in productivity would have necessitated additional process ancillaries such as mixers, mould dividers and packaging lines which would more than double the capital requirements of the installation.[86]
- **Difficulty of retrofit (for a baking oven):** Despite the modular nature of microwave systems, it is prohibitively complex to retrofit an existing baking oven, due to the challenge of addressing microwave leakage. Rather, if microwave baking units are implemented, a new baking oven is usually installed onsite.
- Since microwave heating technologies have been in widespread use in food processing for many decades, **expanding their use beyond its current applications has not been sufficiently explored.**

Innovation needs for the deployment of microwave drying technologies in the food and drink sector:

The primary enabler for microwave drying technologies is the development of comprehensive feasibility studies addressing the barriers listed above.

- **Feasibility studies for effects on product quality:** Concerns of product quality are not unique to electrification technologies. The HyNet industrial fuel switching study for PepsiCo and Kellogg's raised product quality impacts (such as flavour issues) as a key factor when considering the feasibility of switching direct-fired ovens and driers from natural gas to hydrogen.[88] This study noted that the only way to assess the impact would be to run physical testing followed by using the manufacturers' well-established processes to test product quality (e.g., tetrad tests). It is likely that food manufacturers in general would want to complete physical product quality tests to ensure no adverse impacts before adopting microwave technologies, and that these physical product quality tests would need to be bespoke to the product.
- Once product feasibility has been sufficiently proven, **feasibility studies must be carried out for new use-cases of microwave technologies in food processing applications** to assess what process and economic impacts result from its implementation. This will allow sites understand any techno-economic benefits and drawbacks of the technology as well as enable policy makers to assess what policy mechanism can support deployment. The findings from these studies will also carry over to other sectors with similar processes such as some chemical sites.

Drivers for the deployment of microwave drying technologies in the food and drink sector:

- **Microwave heating can dry/bake products much more rapidly than the counterfactual** combustion fired equipment which can lead to an increase in productivity.
- **The footprint of equipment can be reduced since products don't have to spend as long inside the oven/dryers due to the speed at which microwaves heat products.** The system layout is also simplified and doesn't require any handling of combustion products.
- **Microwave heating is highly energy efficient and can reduce the total energy required for drying significantly.** Microwave systems can have efficiencies of 70% and above, while counterfactual gas-fired systems typically operate at efficiencies of ~40%.

5 WIDER BENEFITS AND BARRIERS TO ELECTRIFICATION

The previous sections of this study have explored the specific electrification opportunities and challenges for each of the chosen sectors. In addition to those discussions, there are some benefits and barriers shared across the different sectors that promote or discourage electrification, respectively. Among the benefits, are significantly improved efficiencies and reduced direct carbon emissions. Conversely, some of the barriers include high upfront costs and the significantly higher electricity price compared to the price of natural gas.

5.1 Benefits

Industrial electrification can significantly lower all emissions of carbon and other pollutants. However, electrification can also help to improve the operations of the industrial process itself. Not only can it improve the profitability of the process through higher thermal efficiency but the increased control of the heating process, allowing for higher quality products. Electrification also offers broader energy system benefits and reduces reliance on a single energy source. Further detail is given below:

Environmental – The UK manufacturing sector contributes roughly 16% of all greenhouse gas emissions within the UK. The conventional burning of fossil fuels to generate heat, is responsible for over 50% of industrial related emissions. Furthermore, the burning of fossil fuel also results in the emissions of other air pollutants such as NO_x, SO_x, polycyclic aromatic hydrocarbons, and particulate matter. The electrification of industrial heat eliminates virtually all direct emissions of carbon and air pollutants. With electrification, these emissions will be shifted to scope 2 emissions from electricity generation. In light of the UK's ambition for a net-zero power grid by 2035, these emissions will likely decrease as the grid carbon intensity reduces towards this target, however increased power supply will be needed to satisfy the increasing demand.

Efficiency and product quality – Approximately 20-50% of the total heat released in a traditional fossil fuel combustion process is absorbed and discharged (wasted) by the product flue gases.[3] Electrification technologies, such as electromagnetic and resistive heating, are better able to concentrate heat on the target application, with a higher level of control.[2] This can result in a 30 to 100% improvement of the heating efficiency of electric heating systems compared to natural gas combustion, depending on the heating process and electrification technology.[3] Furthermore, the use of electric heating technologies can result in improvements in product quality and consistency. This is because heat supplied by electricity can be more precisely focussed and is often easier to control than a high-temperature flame.[2]

Operational benefits – In the case of electromagnetic heat technologies, electrification can vastly improve processing times, thereby reducing overall production costs even with higher energy costs from electricity. The manufacturing sector is moving towards more advanced automated and digitised control systems, both of which are well complemented with electric heating technologies. Some electric technologies can be designed in a modular way, for example, resistance heating modules for furnace walls.[46] This potentially allows industrial sites to take a more gradual and convenient approach to electrifying their heating processes. Furthermore, the physical footprint of electrification technologies can often be smaller than conventional combustion systems.

System benefits – electrification offers industrial sites a flexible energy approach, drawing power from diverse range of sources such as solar, wind, or nuclear. This reduces dependency on any single fuel type, enhancing resilience and security of supply. An added system benefit is the potential for pairing storage technologies, particularly thermal energy storage (TES), with electric heating systems. This configuration allows industries to align their energy consumption with times of peak renewable energy output and potentially reduce overall energy costs. It also enables opportunities for an additional revenue stream by providing grid-balancing services to network operators through specific electrification technologies (e.g. electric boilers with very high ramp up rates). Further system benefits may be accessed if electrification is used in processes with particular operating profiles (e.g. batch operation) or thermal energy storage (TES). These use cases enable industrial demand response, unlocking price arbitrage opportunities for industrial sites to save on energy costs, as well as relieve network congestion for system operators.

Dispersed sites – for industrial sites in remote locations (such as those in cement, glass, and food & drink sectors) electrification offers a decarbonisation solution that builds upon existing energy infrastructure more readily accessible to the sites (albeit with a potentially reinforced connection). The sometimes-challenging locations, and lack of ability to share new infrastructure with other industrials (e.g., CO_2 or hydrogen pipelines), may make other decarbonisation solutions such as carbon capture or fuel-switching to hydrogen less accessible or less economical to such dispersed sites.

5.2 Barriers

While electrification offers numerous advantages, several significant current barriers must be tackled. These include the typical barriers for new infrastructure or technology such as high upfront costs, process modification, and supply chain bottlenecks, as well as human-based factors such as lack of knowledge. These barriers are common to many markets, and therefore generic solutions such as financing, incentives, and education may provide the necessary impetus. However, there are other significant barriers associated with the wider energy system such as the high cost of electricity, lack of grid infrastructure, and the relatively low penetration of renewable energy in the overall energy mix. These challenges most likely require centralised government action to create the conditions enabling industrial sites and low-carbon project developers to enact their electrification plans:

Upfront cost – The market penetration of industrial electrification solutions is significantly lower than fossil-fired technologies. As a result, the relevant effects of the technological learning curve as well as a robust supply chain have made it the case that electrification solutions face very high upfront costs to replace existing direct fuel equipment. In some cases, the upfront costs of the electric heating technology are comparable to the fossil-fired counterfactual. However, the capital costs for the required process changes in more integrated industrial processes can be significantly higher than retrofitting the combustion equipment to run on alternative fuels.[89] A further capex barrier for industrial sites is that their combustion heating assets, which have decades-long useful life, are most likely still in the tenure of their operational lifetime. There is thus a disincentive against investing in new heating technologies to avoid significant sunk costs. The industrial energy transformation fund (IETF) is a £315 million fund, created and designed in 2018 to help energy intensive industries reduce their energy costs and carbon emissions through energy efficiency and low carbon technology investments. Apart from the IETF there are no additional support mechanisms for industrial electrification.[90] Despite the recent £185 million expansion of the IETF from 2024, more targeted funding is most likely needed to give the level of support required for the development and deployment of industrial electrification technologies.

Process modification cost – Combustion thermal processes of the 21st century have deployed extensive heat integration updates in their process design and are thus already highly-optimised to maximise overall energy efficiency through waste heat recuperation.[89] In some sectors discussed in this report, such as refining and olefins production, the heating processes use the internally produced waste gas streams from other processes to provide the necessary heating fuel requirements. Electrifying these processes undoes the process's heat integration and creates a surplus of fuel gases. Electrification solutions in this case must seek to find an energetically efficient way to deal with these gases since they carry large amounts of energy. Since electric heat is usually not delivered from point sources such as burners, the redesign of furnace heating chambers may be required to maintain or improve the heating rate and temperature distribution to achieve consistent product quality and processing times. Installing high-voltage electrification technologies may necessitate the implementation of active cooling or electrical isolation to effectively manage power distribution.[89]

Cost of electricity – The cost of heating industrial process is primarily driven by the cost of energy. Currently in the UK, the average cost of electricity for industrial customers is around four times more expensive than the cost of gas fuel for the counterfactual heating processes.[91] This cost-differential is the most predominant barrier preventing the widespread deployment of industrial electrification solutions. Once a power generation asset has been built, the cost of electricity production (or short-run marginal cost – SRMC) is the main driver of its profitability. Wind and solar power require no fuel input to generate power hence they have a much lower SRMC compared to fossil-fired generation which consistently requires (purchased) fuel to produce power. The UK wholesale market price is set by cumulatively stacking the energy provided by different sources of power generation, in order of ascending short-run marginal costs (SRMC), until the demand it met. The price is then set by the cost of generating the last unit of electricity required to meet the demand. This is usually gas-fired power, hence, although the share of renewable capacity has increased from 7% to 37% in the last decade, industrial customers have not felt the cost benefit from this transition. This is because the cost of gas generation sets the price of electricity over 90% of the time despite only comprising 40% of the UK's generation capacity.[90] This fuel cost differential between gas and electricity is further driven by the fact policy costs for social and environmental programs tend to be shifted onto consumer electricity bills.[92]

Innovative options for addressing the issue of high electricity cost

Given the UK ambitions to fully decarbonise the power grid by 2035, the average cost of electricity is likely to decrease overtime. To overcome the barrier of a gas-based marginal wholesale price, 'Green Power Pools' decoupling the cost of gas and renewable energy have been proposed and are the topic of much research.[90] Another area of reform may come from the shifting of carbon tax as well as other environmental and social levies from electricity to fossil-fuels. In addition to the unique advantages available to industrial sites that switch to electric heating technologies, these reforms would ensure better cost parity between the fuel-costs of gas-fired and electric assets. It must be noted however that reforms shifting policy costs from electricity to gas may negatively impact industries in which electrification pathways are still in the early stages of development.

Grid infrastructure – large-scale electrification projects rapidly increase the connected load seen on the network. In grid-constrained areas, a single electrification project could necessitate significant investments through new substation transformers and other grid reinforcement measures. For the industrial site, electrification could mean an altogether new grid connection that needs to be applied for. The cost of a new connection is primarily dependent on the network voltage level that the industrial site will be connected to, as well as the distance from the network to the site.

Grid connection requirements for the paper industry

The Confederation of Paper Industries (CPI) in partnership with Fichtner Consulting Engineers evaluated the necessary grid connections and local infrastructure requirements to facilitate the electrification of paper mills in the UK.[93] It was assumed that the thermal demand, currently met by gas-CHP, would be replaced by the electrification of the boiler. It was not clear which technology, but the assumption seemed to be a one-to-one replacement of the thermal demand with electrical demand, which in effect implies the use of an electric boiler. In light of this, the study contained the following key findings:

- Electrifying the current thermal demand in UK paper mills will result in a three to fivefold increase in the electrical load of the paper mill.
- Approximately two thirds of the sites investigated would require a degree of grid reinforcement, through an alternative or higher voltage substation.
- This study claimed a 12-to-24-month lead time to process and install new connection applications to the local DNO.
- It was found that full electrification of the UK paper industry would result in a 1.2 GW increase in the electrical load, costing £275M for all 47 sites in grid connections (this excludes the capex of the electric heating asset).

Furthermore, grid connectivity is increasingly becoming a key challenge to UK's energy networks and a growing barrier to address to achieve the ambitious decarbonisation plans set out by the UK government. There is a rapidly accumulating pipeline of low carbon projects on the supply and demand side. Considering the large permitting backlog in UK energy networks for new grid connections, the five-to-ten-year delays caused as a result may create too significant a time delay between initial capital investment and operation of the technology, potentially extending the payback period beyond investor tolerance.[94]

Lack of knowledge – Electric heating technologies must compete with counterfactual fossil-fired processes that have been used for decades and in which there is a deep field of knowledge and expertise across the value chain. Although some of the most promising electrification technologies are well-established from a technological perspective, they are not seen as reliable by some parts of the industry, thus limiting their deployment. The lack of comparative expertise across the value chain increases the perceived risk and creates the impression amongst industrial companies that some electrification technologies are not mature or suitable for use in their processes.

While electrification technologies are generally simple with reduced maintenance requirements, the knowledge and education of industrial engineers, technicians and contractors can be a barrier to industrial electrification. New electrification technologies require a retraining of employees/contractors to ensure best practices are used in process control, maintenance, and safety.

Electrification value chain – Industries are becoming increasingly aware of the opportunity electrification technologies bring to decarbonising their heating processes. In this, there may be a potential supply chain risk for certain mature electrification technologies (like heat pumps and electric boilers) which may see a rapid increase in demand from industries. Since there are a reduced number of local (UK) suppliers for these technologies, the widespread deployment of electrification technology will be contingent of the speed of development of the local electrification value chain.

Limited renewable penetration – Although electrification eliminates all Scope 1 emissions of greenhouse gases and pollutants, its broader decarbonisation potential in the UK is contingent on the grid carbon intensity. With the current power generation mix, the average grid carbon intensity is 207 gCO_2e/kWh_e. The UK is forecasted to deploy an additional 143 GW of renewable generation capacity by 2035 to achieve a net-zero power grid.[95] However, there is still concern on whether this is practically achievable due to the growing backlog of renewable projects that have not yet received permits. With some of these projects facing delays of up to 10 years, the potential for electrification to achieve the deep decarbonisation needed is hindered unless the UK energy networks can address this issue in the short-term.

Competing decarbonisation pathways in industrial clusters – The UK Government CCUS Cluster Sequencing programme may act as an incentive for sites within industrial clusters to preferentially deploy carbon capture or fuel-switch to hydrogen, as an alternative to electrification. This is both due to the ability to access shared transport and storage infrastructure, and the potential opportunity for subsidies via the UK Governments CCUS Business Models.[53]

6 RECOMMENDATIONS

There is a breadth of opportunities for UK industry to significantly lower emissions via electrification technologies. Considering the six industrial sectors investigated within this study, the vast majority of emissions were associated with combustion of fossil-fuels for heat generation, with temperature requirements ranging from less than 100°C to more than 1000°C. Established techniques exist to generate such temperature ranges electrically, including heat-pumps, resistive heating, electromagnetic radiation, and electric arc. While currently the applications of such techniques to specific industrial processes is limited, this study identified that in many areas there exists ongoing research to demonstrate and commercialise electrified heating solutions. Furthermore, some heating applications (such as steam generation) already have a commercially available electric option (in the form of heat-pumps or electrode boilers) with barriers to deployment mainly being economic rather than technical.

To enable the electrification of UK industry, this study identified sector specific recommendations that have been summarised in the table below, which has been ordered by highest TRL and then applicable UK emissions. These are characterised into three categories:

Research needs: indicates where additional technical modelling, research, and development would be useful to support electrification of the process and its site integration (e.g., optimal design configurations, novel material development, simulations, lab testing or small-scale pilot)

Demonstration needs: indicates where larger, potentially first-of-a-kind, deployments are needed to demonstrate the capabilities of the electrification solution on an industrially relevant scale as well as demonstrating integration of the solution into wider site operations

Wider needs: indicates further actions specific to the sector or technology that are needed to support commercialisation or wider uptake of electrification solutions, such as raising awareness or researching knock-on impacts

Opportunity • *Electrification equipment* • *TRL* • *Estimate of applicable UK emissions**	**Recommendations to enable opportunity**	
Cross sectoral: Electric boilers for steam generation – cross sectoral TRL 9 *3.5 $MtCO_2$*		• None, technologies meeting requirements are commercially available
		• Demonstrate electrode boilers in industrial applications with high-pressure steam requirements to improve awareness and confidence in high-pressure capabilities
		• Raise wider industry awareness of the capabilities of element and electrode boilers for low and medium pressure steam generation
		• Use computational modelling to guide electrode placing to maintain stable thermal flows as furnace size and electrode spacing increase

*Estimated combustion related emissions attributed to each industrial process, following adaptations from 2021 reported emissions data (NAEI large point sources)

Glass: Resistance furnace for glass melting TRL 9 *1.2 $MtCO_2$*		• Use computational modelling to further understandings on the mode of corrosion attack on refractories in electric furnace. Use this information to guide maintenance strategies for maximising furnace lifetime • Continue developing refractory materials with a strong focus on corrosion and wear resistance for application in electric furnaces
		• Support UK demonstration projects to provide learnings and develop skills around wider integration of technologies into existing facilities
		• Improve awareness of the capabilities and benefits of cold-top vertical melting furnaces and hybrid glass melting furnaces • Raise awareness that the smaller capacities of CTVM furnaces presents an opportunity for multiple smaller furnace installations, providing improved process flexibility and economic feasibility of operation.
Food & drink: microwave dryer for oven/dryer TRL 8 – 9 *0.6 $MtCO_2$*		• Support application specific testing (e.g., lab and pilot projects) to establish the suitability of microwave heating for specific product applications, specifically with regards to understanding the impact on product quality • Identify any techniques that can be employed to complement microwave technologies in meeting specific product quality requirements
		• While technologies are already established, incentivising sites to become early adopters could enable the development of learnings and skills around wider integration of technologies into existing facilities
		• Support Food & Drink sites in assessing the feasibility of electric solutions (especially microwave) for their specific site and product
Paper: High-temperature heat pumps (and MVR) for steam generation TRL 7 – 9 *1.0 $MtCO_2$*		• Continue to research blends of low-GWP refrigerants to optimise heat pump performance • Conduct further research into existing industrial MVR installations to further the integration of heat pumps and MVR systems. This will act to elevate the maximum steam temperature and pressure that heat pump systems can provide
		• Demonstrate the use of high-temperature heat pumps at scales relevant to the paper industry (10s of MW_{th}) • Demonstrate the use of high-temperature heat pumps at UK paper sites to identify learnings around site-integration and increase experience
		• Exploit opportunities to deploy commercially available heat pump products by supporting the paper industry to identify appropriate products that meet site-specific requirements
Olefins: Electric cracker for pyrolysis steam cracking TRL 6 *2.4 $MtCO_2$*		• Conduct further research into the design concept for an electric cracking reactor, including testing to ensure heating profile meets final product yield and quality requirements
		• Monitor the results of current first-of-a-kind (FOAK) consortium projects to establish further areas of technological development 1. BASF, SABIC, Linde (Germany)

(other abatement routes may be more suitable due to internal fuels and wider steam integration of plant)		2. Shell and Dow (Netherlands) 3. LyondellBasell, Technip and CPChem (USA)
		• Identify alternative uses for the by-product fuel gases to support the case for electrification (in comparison to carbon capture) • Explore how implementation of electric crackers may impact wider plant operations (e.g., plant steam balance) and establish what additional measures may be needed to support integration (e.g., steam import)
Refining: Resistance furnace for atmospheric distillation unit TRL 6 *1.2 $MtCO_2$* (carbon capture identified as potentially more suitable abatement route due to internal fuels consideration)		• Conduct further research into the design concept for integration of resistive heating into the ADU process, and deploy pilot-scale trials to validate this and improve TRL (currently TRL 6) • Explore the impact of heating element oxidisation at high temperatures on lifetime and maintenance requirements
		• Monitor outcomes of wider demonstration projects linked to high-temperature electric resistive heating (e.g., steam cracking) • Following further technical research, conduct demonstration projects that show integration of resistive heating into atmospheric distillation units
		• Identify alternative uses for refinery off-gases to support the case for electrification (in comparison to carbon capture)
Cement: Electric arc calciner for calcination and sintering TRL 5 - 6 *1.8 $MtCO_2$* (would be deployed alongside carbon capture solutions, enabling higher purity capture of process emissions from calcination)		• Scale-up the design of individual reactors to meet requirements of current production levels with a realistic number of units - developments in the scale of plasma arc torches may facilitate this • Research the potential for plasma arc torches to contribute to emissions reduction on existing assets (e.g., via modelling and pilot projects)
		• Monitor outcomes of wider demonstration projects linked to electric arc calciners such as the SaltX Electric Calciner Research Centre
		• Improve awareness around electrification technologies in cement through targeted studies to provide a strong demand signal that incentivises research and development in this technology

In addition to sector or technology specific needs, **wider barriers to electrification should be addressed** to support deployment of electric decarbonisation solutions across UK industries. These include **reducing the upfront and operational costs, grid infrastructure upgrades, skills and supply chain developments, and knowledge building** across industry. These factors were not a focus of the current study, where the scope was limited to a technical assessment of electrification equipment. Further work is therefore needed to better understand the wider barriers and benefits for electrification, and the wider enabling actions that could support uptake. Recommendations for further work based on the potential wider barriers and benefits identified in this study are included below.

Recommendations for further work

- **Development of competitions for industrial feasibility and demonstration projects of electrification technologies.** This report sets out areas where developments in industrial electrification could be supported through further research, demonstration projects, or wider activities such as awareness building. Further work is needed to design UK incentives to encourage both research in and demonstration of electrification technologies. Some government competitions already include electrification, such as the Industrial Fuel Switching Competition; however, others, such as the UKRI Industrial Decarbonisation Challenge, have selected projects mainly focused on CCUS and hydrogen.

- **Wider engagement and dissemination activities to raise awareness.** This report identifies awareness of electrification solutions and lack of knowledge around electrification as a barrier to scale-up, even for technologies that are commercially available. Further work is needed to improve UK industry's understanding of electrification opportunities for different sectors. This could include conducting an awareness campaign or hosting electrification focused conferences, supporting industrial stakeholders and technology developers to connect.
- **Reviewing the role of electrification compared to hydrogen and carbon capture considering geographic context.** This report identifies that some technologies are not being demonstrated at industrial scales due to a lack of demand signals from industry to incentivise such activities. Developing a clear understanding of the expected role of electrification across sectors (such as setting targets for uptake) could provide a signal to technology developers to target such industrial applications. Furthermore, when evaluating the relative role of industrial electrification compared to other solutions for a sector (e.g., hydrogen, biofuels, or CCUS), the geographic context should be considered. The role of industrial electrification in dispersed sites or inland clusters (such as the Black Country) may differ to that in shoreline industrial clusters, due to differences in accessing shared CO_2 and hydrogen infrastructure.
- **Mapping the scale and geographic distribution of future electricity demands for industry across the UK.** Developing a dataset of future electricity demands from industry with high spatial-granularity would help to support district network operator analysis on infrastructure upgrades as well as wider analysis on the potential for electrified industries to provide load-balancing services.
- **Evaluating opportunities for electrified industrial processes to provide load-balancing services to the grid.** To understand opportunities for different industrial sectors to provide load-balancing services, there is a need to better understand the operating schedules of these sectors, identify whether electrified items of equipment could feasibly be turned-up/down on demand, over what timeframes or notice, and any cost or productivity implications of such activities. Additionally, further work to assess how electricity demand-profiles from industry could vary on a daily, weekly, and seasonal basis would be useful for understanding the impact on the energy system.
- **Evaluating the infrastructure implications of industrial electrification, including the need for grid reinforcement and energy storage systems.** Once potential industrial electricity demands have been mapped, further work will be needed to understand the potential requirements for grid reinforcement to connect industrial sites with renewable electricity generation. Furthermore, work will be needed to understand interactions between operating schedules, load-balancing services, and the need for energy storage systems to ensure that industry has a reliable supply of renewable and affordable electricity.
- **Review of grid connection costs, timelines, and other connection challenges for industry to identify enabling actions.** A review is needed into current challenges faced by industrial sites wanting to upgrade grid connections, including timelines and connection costs, to better understand these barriers. This should be conducted alongside engagement with district network operators to identify solutions to these challenges.
- **Identifying the impact of electricity prices on the economics of industrial electrification, and developing recommendations for electricity market pricing or policy support mechanisms to incentivise uptake.** The cost of electricity relative to gas is expected to be a significant economic barrier for electrification technologies. Further work analysing the techno-economics of electrification technologies, considering efficiency improvements alongside energy prices, under different energy pricing models is needed. This analysis could provide

recommendations for how electricity market arrangements could enable industrial electrification. Such analysis could also support the development of ‘business models’ that enable the uptake of electrification, similar to the government’s CCUS and hydrogen production business models.

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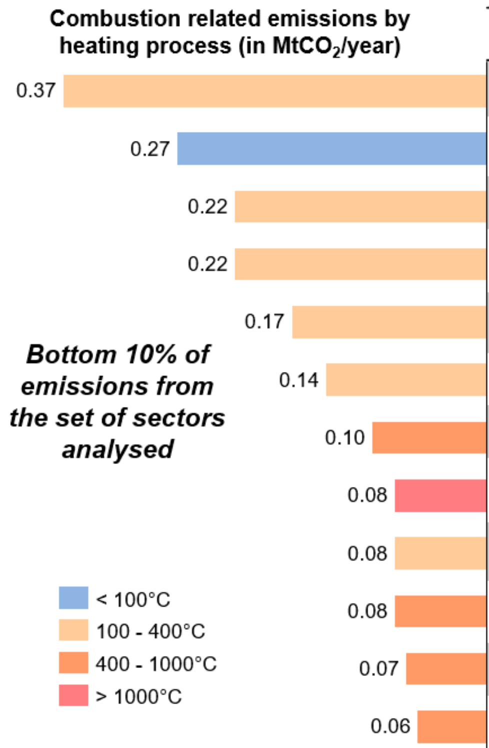
APPENDIX

Table 4: Original shortlist for process archetyping, subsequently refined to 10 sectors

	ERM Subsector	NAEI Sector	SIC code	Emissions ($ktCO_2e/year$)	# sites
1	Oil refining	Processing & distribution of petroleum products	19201	9,932	8
2	Integrated steel site	Iron & steel industries	24100	8,437	2
3	Integrated cement kiln	Cement	23510	5,821	11
4	Olefins	Chemical Industry	20140	2,785	4
5	Paper mill	Paper, printing & publishing industries	17120	1,430	38
6	Glass	Other mineral industries	23110 – 23190	1,290	21
7	Fertiliser and Nitrates	Chemical Industry	20150	1,156	2
8	Other chemicals	Chemical Industry	20110 – 20600	1,084	40
9	Lime production	Lime	23520	1,046	5
10	Other food	Food, drink & tobacco industry	10612 – 10730	1,256	89
11	Inorganic basic chemicals	Chemical Industry	20130	884	14
12	Bricks	Other mineral industries	23320	864	48
13	Other minerals	Other mineral industries	23110 – 23190	554	90
14	Vehicle parts	Vehicles	29100 – 29300	435	27
15	Pharmaceuticals	Chemical industry	21100	318	20
16	Dairy	Food, drink & tobacco industry	Incl in Other food	225	21

Given the process diversity of the “other chemicals”, “other minerals” and “pharmaceuticals” sectors, it is challenging to archetype these sectors and therefore establish specific processes of interest for electrification. Some the specific chemical processes from these sectors included via other shortlisted chemical sectors: olefins, inorganic chemicals, and fertiliser & nitrates. Furthermore, the “other food” and “dairy” subsectors were combined and archetyped as one “Food” sector. Lastly, it is noted that a significant proportion (over 60%) of emissions from lime production are process emissions from the calcination of limestone and consequently lime production does not actually fall in the top 10 NAEI sectors for fuel-related emissions. However, lime kilns are used in the “paper mill” subsector, therefore these processes are included in the analysis despite the exclusion of the “lime production” subsector. Integrated steel sites were excluded since the two large steel sites in the UK (Scunthorpe and Port Talbot) are likely to have already set their future decarbonisation strategies.



Heating Process	Electrification technologies
Hydrocracking	Resistance Furnace
Thermal Drying	Electric / Microwave / Infrared Dryer
Vacuum Distillation Unit	Resistance Furnace
Polymer Melt / Extruding	Electric / Microwave / Infrared Dryer, Electric Reactor
Brick Drying	Electric Dryer
Haber-Bosch Reactor	Centrifugal Compressor Reactor
Annealing Furnace	Resistance Furnace
Foundries	Induction Furnace, Resistance Furnace
Thermal Cracking / Visbreaking	Resistance Furnace, Plasma Furnace
Cracker	Electric Cracker
Reformer	Electric Reformer
Paper Lime Production	Electric Arc Calciner

Figure 28: Depiction of combustion heating processes, their CO_2 emissions, and the associated electrification technologies to abate these processes.

Table 5: Table showing combustion heating processes, their CO_2 emissions, and the associated electrification technologies to abate these processes.

Temperature	Heating Processes	Electrification Technologies	Combustion emissions ($MtCO_2$ / year)
< 100°C	Space Heating	Compression Heat Pump, Electric Boiler	0.88
	Thermal Drying	Electric / Microwave / Infrared Dryer	0.27
100 – 400°C	Steam Generation	Compression Heat Pump, MVR, Electric boiler	3.53
	Ovens	Microwave / Infrared Dryer	0.63
	Polymer Melt/ Extruding	Electric / Microwave / Infrared Dryer, Electric Reactor	0.22
	Brick Drying	Electric Dryer	0.17
	Haber-Bosch Process	Centrifugal Compressor Reactor	0.14
	Atmospheric Distillation Unit	Resistance Furnace	1.22
	Vacuum Distillation Unit	Resistance Furnace	0.22
	Hydrocracking	Resistance Furnace	0.37
	Thermal Cracking/ Visbreaking	Resistance Furnace, Plasma Furnace	0.08
	Catalytic Reforming	Resistance Furnace	0.47
400 - 1000°C	Clinker Pre-heating	Resistance Kiln	0.66
	Cracker	Electric Cracker	0.08
	Reformer	Electric Reformer	0.07
	Paper Lime Production	Electric Arc Calciner	0.06
	Annealing Furnace	Resistance Furnace	0.10
	Brick Firing Kiln	Resistance Kiln, Microwave-assisted Kiln	0.65
	Hydrogen Production SMR	Resistance Furnace	1.15
	Pyrolysis Steam Cracker	Electric Cracker	2.37
> 1000°C	Calcination and Sintering	Plasma Furnace, Electric Arc Calciner	1.84
	Glass Melting Furnace	Resistance Furnace	1.19
	Foundries	Induction Furnace, Resistance Furnace	0.08

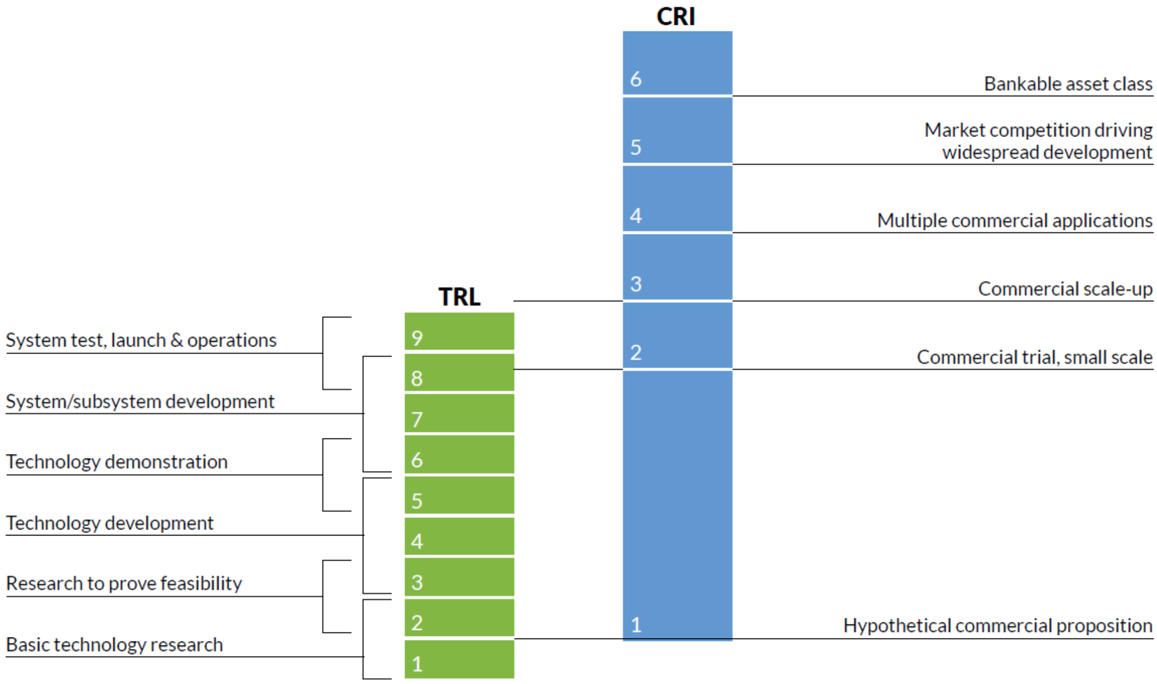


Figure 29: Technical readiness level and Commercial readiness indicator.[1]

Table 6: Table showing the energy balance for a generic paper mill[23]

Process unit	Electricity use (MW_e)	Steam use (MW_{th})
Stock Production	3.8	0.0
Paper machine – Wire section	1.6	0.0
Paper machine – Press section	2.0	6.5
Paper machine – Dryer section	2.9	31.6
Paper machine – Calender section	0.22	1.4
Ancillaries	11.8	7.0
Total	22.3	46.5

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